ARMY RESEARCH LABORATORY

Improved Rolled Homogeneous Armor (IRHA) Steel Through Higher Hardness

by Joseph Prifti, Michael Castro,
Richard Squillacioti, and Raymond Cellitti

ARL-TR-1347 April 1997

Abstract

An improved rolled homogeneous armor (IRHA) steel with enhanced ballistic performance has been developed. Increases in ballistic performance are attributed to higher hardness levels achieved by IRHA, which maintain adequate toughness and ductility. Through augmentation of a generic chemical composition for standard rolled homogeneous armor (RHA) material, and optimization of heat treatment, greater hardenability, and higher hardness levels were attained. The higher hardenability ensures that through-thickness hardness, with the desired martensite microstructure, is obtained for armor plates up to 3 in thick, using current steel mill facilities and practice. The optimal, relatively low-carbon, nickel-chromium-molybdenum (Ni-Cr-Mo) IRHA alloy was developed in-house, employing U.S. Army Research Laboratory (ARL), Materials Directorate (MD) laboratory facilities, followed by steel mill production heats demonstrating scale-up and producibility. Ballistic testing vs. projectiles, ranging from medium caliber to tank rounds, established that the IRHA material at the HRc 40 hardness level is best suited for vehicle hull applications, while material at HRc 48 provides better protection as applique armor. The armor plate at both hardness levels (HRc 40 and 48) demonstrated structural integrity upon high kinetic energy (KE) ballistic loading, through passing the required full-scale 105-mm armor piercing (AP) T182 projectile impact tests. At the HRc 40 level, the IRHA weldability and fabricability were shown to be comparable to standard RHA for tank construction.

Executive Summary

This program was conducted by the Materials Directorate (MD) (Watertown, MA), U.S. Army Research Laboratory (ARL), for the Program Manager, Survivability Systems (PM-SS), and the U.S. Army Tank Research, Development, and Engineering Center (TARDEC) (Warren, MI). The overall goal of the effort was to increase the ballistic performance of rolled homogeneous armor (RHA) (MIL-A-12560)* steel by achieving higher hardness levels while maintaining structural and welding requirements for the main battle tank. Furthermore, it was desired that the improved material be produced at little or no increase in cost relative to the standard RHA plate.

The program proceeded through an iterative process toward development of an optimal RHA chemical composition and associated heat treatment utilizing metallurgical analysis and extensive ballistic testing. Much of the research was conducted on laboratory-scale material obtained from 800-lb heats of steel produced in-house. This was followed by steel mill production heats to demonstrate scale-up and producibility.

Two conventional RHA relatively low-carbon alloy systems (nickel-chromium-molybdenum [Ni-Cr-Mo] and manganese-molybdenum-boron [Mn-Mo-B]) were investigated. These alloy systems have been used for the production of RHA steel over the past 40 years. It was determined that the Ni-Cr-Mo system, through alloying element augmentation, was most amenable to achieving the goals of the program. The optimal chemical composition developed for the improved RHA (IRHA), in weight-percent, is carbon - 0.26, nickel - 3.25, chromium - 1.45, molybdenum - 0.55, manganese - 0.40, silicon - 0.40, and impurities: phosphorous <0.010 and sulfur <0.005, with the remaining material being basically iron (93.68). The hardenability index for this optimal IRHA alloy chemistry is in the 9.0–10.0 range, allowing for normal alloying element variations consistent with steel mill practices. Hardenability of steel is defined as that property that determines the depth and distribution of martensitic hardness induced by quenching. For this program, it was important that the hardenability index be high enough to ensure through-thickness hardness for steel plates up to

* U.S. Department of Defense. "Armor Plate, Steel, Wrought, Homogeneous." MIL-A-12560, Washington, D.C.

3 in thick. The IRHA alloy produces plates with the desired martensitic structure of over 99% for quench cooling rates as low as 0.88° F/s that are well within existing steel mill capability and practice.

To ensure that the desired metallurgical properties are obtained for the up-alloyed IRHA material, it was determined that the following heat treatment of the rolled armor plate be required: (1) normalize at 1,700° F and air cool; (2) austenitize at 1,625° F and water-quench; and (3) temper at 985° F to obtain plates at Rockwell C hardness (HRc) 40 and temper at 425° F for plates at HRc 48. Plates tempered to these hardnesses maintained Charpy impact strengths greater than 20 ft·lb, a measure of the material's toughness upon ballistic loading.

The IRHA plate at the HRc 40 level is the preferred material for vehicle structural armor applications, providing the best overall ballistic performance vs. the broad spectrum of projectile-fragmentation threats and fabricability considerations. Although both the HRc 40 and 48 plates passed the full-scale 105-mm armor-piercing (AP) T182 projectile impact "crack resistance to ballistic shock-loading" test, the HRc 40 material exhibited little or no cracking. It was also demonstrated that weldability and machinability of the HRc 40 plate are comparable to standard RHA, and welded H-plates passed the ballistic impact test requirements. The carbon content was maintained at 0.26% or less (similar to standard RHA) for the IRHA alloy to preserve the weldability characteristics of the material.

For applique-type armor, IRHA at the HRc 48 level provides better protection against conventional hard-core AP projectiles and heavy metal penetrators. At this hardness level, the IRHA can also be employed as an improved surrogate for the current high-hardness steel armor applications procured under MIL-A-46100.*

* U.S. Department of Defense. "Armor Plate, Steel, Wrought, High Hardness." MIL-A-46100, Washington, D.C.

In accordance with established guidelines for the program, the increase in cost for the IRHA, including up-alloying and modified heat treatment, is approximately 10% or 8¢/lb for the finished plate.

INTENTIONALLY LEFT BLANK.

Acknowledgments

This effort involved the work and support of numerous individuals to whom the authors express their appreciation. First, for financial support and understanding, they thank Messrs. Terrance Dean and John Rowe, Office of the Program Manager, Survivability Systems (PM-SS), and Drs. James Thompson and Samuel Goodman at the U. S. Army Tank Research, Development, and Engineering Center (TARDEC) (Warren, MI).

The authors also thank Messrs. Dino Papetti (Chief, Armor Systems Team), Arthur Ayvazian, and Anthone Zarkades from the U.S. Army Research Laboratory, Materials Directorate (ARL-MD) (Watertown, MA) for initiation of the program and the many ensuing technical discussions. A special thanks is given to Messrs. Robert Grossi and George Dewey for the preparation of numerous 800-lb heats of steel, followed by electroslag refining (ESR) processing of the cast ingots. Slabbing, rolling, and heat treatment of hundreds of experimental test plates could not have been accomplished without the dedication and expertise of Messrs. Francis Hanrahan and Mark Taylor.

The authors also wish to thank Messrs. Thomas Melvin and James Catalano for their contribution in performing weldability testing of the improved rolled homogeneous armor (IRHA) at ARL (Watertown, MA) and for their assistance in coordinating the efforts and monitoring the General Dynamics Weldability Testing Program.

Engineering services provided by Mr. Patrick Woolsey and expeditious performance of ballistic tests by Messrs. James Brown and David Kokidko were key to the program's success. The authors also thank Dr. William Bruchey and Mr. Edward Rapacki (ARL-Weapons Technology Directorate [WTD]) for their input and monitoring of full-scale ballistic testing and evaluation, and Messrs. Gary Rowe and Dennis Greenland, U.S. Army Aberdeen Test Center (ATC), for their resourcefulness in conducting full-scale ballistic shock-load tests.

Mechanical test specimen preparation was accomplished by a number of machinists, most notably, Messrs. Leonard Bucciarelli and George Vangel. Mechanical testing was expertly

performed by Ms. Karen Harvey and Mr. Wayne Bethoney. A special commendation goes to Mr. Dennis Gosselin for his many services contributing to mechanical properties and ballistic testing.

Finally, thanks go to Dr. Morton Kliman for his encouragement and assistance in the preparation of this final report.

Table of Contents

INTENTIONALLY LEFT BLANK.

List of Figures

Figure | Page

List of Tables

INTENTIONALLY LEFT BLANK.

1. History and Introduction

Homogeneous wrought steel armor was introduced over 80 years ago on the first tanks developed by the U.S. Army. Early tanks were of riveted construction and employed low-carbon, medium-alloy steels of special compositions. During World War II, rolled homogeneous steel underwent an important variation due mainly to alloy conservation priorities brought about by the conflict. The resulting armor was based on a low-alloy material with low-carbon content possessing adequate toughness (Laible 1980). Although welding technology was developed for rolled steel plates, the use of cast steel prevailed for tank structures, providing further reductions in cost and increased production capability. The use of cast steel for hulls and turrets continued for the next 25 years, most notably for the M60 tank. During recent decades, due to cost-saving fabrication techniques and more complex vehicle configurations, rolled homogeneous armor (RHA) steel has supplanted cast steel, as demonstrated by the M1 Abrams tank. Based on cost considerations, RHA steel is now, and will continue to be, the principal material employed for heavy combat and recovery vehicles. Although improvements in steel processing and production have evolved since World War II, the material covered by the RHA specification (MIL-A-12560 [U.S. Department of Defense]) has not appreciably changed, providing little or no improvement in ballistic protection.

Historically, the intellectual basis for improving steel armor ballistic performance has been to increase the hardness of the steel without causing an increased tendency to fail by brittle fracture. During the 1970s and 1980s, developmental efforts were undertaken that proved unsuccessful in attaining all the ballistic and structural requirements (Ayvazian and Papetti 1973; Papetti 1978; Campbell and Ayvazian 1985). The important lessons learned included (1) steel armor plates possessing hardnesses in excess of Rockwell C hardness (HRc) 52 could not retain structural integrity when impacted by full-scale-caliber kinetic energy (KE) rounds; (2) the hardened steel must demonstrate a V-notch Charpy (CHV) impact value greater than 20 ft·lb measured at $-40°$ F; and (3) the reduction of steel plate thickness (or reduced weight) is not necessarily achievable from higher performing material. It is also axiomatic that an improved RHA (IRHA) steel must retain excellent weldability and fabricability commensurate to the standard RHA per requirements of MIL-A-12560.

Based on the aforementioned information and a consensus of the U.S. Army's armor experts, this effort was undertaken to determine the higher hardness levels attainable with corresponding improvement in ballistic performance for RHA steel, while maintaining all the structural requirements. The enhancements would be achieved through metallurgical alloy modification, processing, and heat treatment. The developmental work was accomplished in-house at the U.S. Army Research Laboratory (ARL), Materials Directorate (MD) (Watertown, MA site), utilizing a laboratory-scale foundry, forging and rolling equipment, heat-treating facilities, and a wide range of metallurgical and engineering services.

2. Program Rationale

The program rationale was to proceed by an iterative process to ballistically improve current RHA steel through higher hardness by alloy chemistry modification and heat treatment, while maintaining the structural integrity of the material. Furthermore, the necessity to retain comparative cost effectiveness would permit only strategic alloying additions while utilizing processing and heat-treatment facilities essentially similar to standard RHA production practices. To ensure the retention of comparative weldability, the carbon content was to be within the 0.24%–0.28% level (with an aim of 0.26%). This is the same as RHA material employed in current tank production facilities.

A survey of steel producers' technical data sheets from 1980 to 1990 confirmed that two relatively low-carbon alloy systems are employed for the standard RHA material. These are the manganese-molybdenum-boron (Mn-Mo-B) alloy and the nickel-chromium-molybdenum (Ni-Cr-Mo) alloy systems. In general, the practice is to utilize the Mn-Mo-B alloy for plate thicknesses 1.5 in and less, and the Ni-Cr-Mo alloy for the thicker gauges. However, both alloys can be found in the RHA inventory across the thickness range of interest; namely, 3/4 in through 3 in. (This effort did not consider thicknesses less than 3/4 in since the thinner gauges are of higher hardness per MIL-A-12560, and that only marginal improvements in ballistic performance could be realized with further incremental increases in hardness.) For this program, both alloy systems were investigated.

The first step was to utilize off-the-shelf RHA material and increase the hardness through conventional heat treatments to determine the level of enhanced ballistic performance achievable. This procedure would yield the most cost-effective material. The next phase would require using both alloy chemistry modification and heat treatments. An optimum alloy composition was developed, utilizing relatively small (800 lb) in-house steel heats at ARL-MD (Watertown). This was followed by full-scale industry production heats. Concurrently, ballistic test and evaluation would first involve medium-caliber threats in accordance with the requirements of MIL-A-12560 to be followed by large-caliber (tank-type) KE projectile threats.

Metallurgical, chemical, and microstructural analyses, along with precise mechanical property characterization, were significant elements in the iterative developmental process. Careful consideration was given to the various steps in the processing of in-house steel heats, including rolling, heat treatment, quenching, tempering, etc., with the intent of achieving similar material with the production heats by major steel producers. With constantly improving steel melting and processing practices, over twenty 800-lb steel heats were produced in-house under careful control. The information gained gave rise to two moderately sized (15 and 40 ton) production heats at the Jessop Steel Company and eventually culminated in a full-scale, 200-ton production heat at the U.S. Steel (USS) facility at Gary, IN.

3. Mn-Mo-B RHA Alloy

3.1 Heat Treatment and Metallurgical Analysis. The initial program iteration explored the use of conventional RHA (off-the-shelf material) processed to higher hardness levels than required in the current MIL-A-12560 specification. Higher hardness levels were to be achieved by simply optimizing the heat treatment and thereby obtaining the most cost-effective material with improved ballistic performance.

The first set of experiments focused on 1 1/2-in-thick RHA plates possessing the Mn-Mo-B alloy chemistry as given in Table 1. This thickness was chosen as being in the midrange for tank applicability. As noted earlier, steel producers tended to employ the Mn-Mo-B alloy for RHA

Table 1. Chemical Composition of Mn-Mo-B Alloy RHA Steel[a]

Source[b]	C	Mn	Mo	B	Si	P	S	Cr	Ni
CHT	0.28	1.54	0.50	0.0011	0.23	0.008	0.008	—	—
ATC	0.26	1.30	0.50	0.0007	0.28	0.017	0.002	0.016	0.100

[a] weight-percent.
[b] 1 1/2-in-thick RHA plate per MIL-A-12560.

thicknesses 1 1/2 in and less. Material was obtained from the RHA stockpile at the U.S. Army Combat Systems Test Activity (CSTA),* Aberdeen Proving Ground (APG), Maryland, and procured from Canadian Heat Treat (CHT), Ontario, Canada. Within this time frame (1989–1992), CHT was the only producer of RHA in North America. As shown in Table 1, the chemistries for RHA plates from these two off-the-shelf sources were comparable; with the CHT material possessing slightly higher carbon and boron contents. Processing of the plate material at ARL-MD (Watertown) consisted of reheat treatment by thorough austenization at 1,650° F, followed by a water quench, and then complete tempering at various temperatures from 400° F to 900° F. Table 2 summarizes the hardnesses and CHV impact values (measured at −40° F) obtained at each tempering temperature. As expected, higher hardnesses were achieved with the higher carbon content (0.28%) CHT material; however, the Charpy values were similar for both lots of material. Figure 1 provides these results in a graphical form that displays the conventional linear hardness and parabolic-type relationship of CHV impact energy (at −40° F) vs. tempering temperature, with the trough or temper embrittlement range occurring between 450° F and 750° F. The highest Charpy values were obtained at the 900° F temper with the optimal combination of higher hardness and Charpy values produced at the 400° F temper. Examination of photomicrographs, and the fact that an HRc 49 was achieved for the as-quenched 0.28% carbon plate, confirmed that the material was basically 100% martensite. It is an accepted fact that tempered martensite is the most desirable condition for steel armor plate.

* Now the U.S. Army Aberteen Test Center (ATC).

Table 2. Hardness and Charpy Impact Toughness for Mn-Mo-B RHA Material Through Conventional Heat Treatment

Tempering Temperature (°F)[a]	Hardness Level (HRc)		Charpy Impact at −40° F (ft·lb)[b]			
			CHT		ATC	
	CHT	ATC	LT	TL	LT	TL
400	49.1	45.0	18.0	17.0	17.7	12.2
500	46.8	43.8	13.7	13.0	11.8	11.6
700	43.9	—	10.7	11.3	—	—
800	41.0	38.1	11.5	10.5	17.0	11.8
900	38.3	35.6	24.8	25.3	34.7	20.8
275[c]	49.0	—	15.5	15.0	—	—

[a] 1 1/2-in-thick plate material austenitized at 1,650° F for 2 hr and water-quenched prior to tempering.

[b] CHV specimens machined with longitudinal-traverse (LT) and transverse-longitudinal (TL) plate orientation. Charpy values are an average of three readings. Measurements were obtained with a 240-ft·lb Satec machine.

[c] 1 1/2-in-thick plate material received in as-quenched condition from CHT that had been stress-relieved draw-tempered at 275° F.

3.2 Ballistic Test and Evaluation. Ballistic test results for both lots of material vs. the 20-mm armor-piercing incendiary (API) M602 projectile are provided in Table 3. The 20-mm API M602 tungsten carbide core projectile is specified in MIL-A-12560 for acceptance testing of RHA within the 1.125-in–2.75-in thickness range. The test results are indicative of steel armor performance against hard and relatively brittle penetrators (tungsten carbide and hard steel) with improved performance achieved by the higher hardness RHA material. The best performance was achieved at the HRc 49 level, obtained by tempering the RHA material at 400° F. It should be noted that this modest increase in performance (V_{50} of 2,612 ft/s relative to 2,404 ft/s for conventional RHA) was achieved for material possessing a Charpy impact value of 18 ft·lb, which is considered borderline for toughness of structural armor.

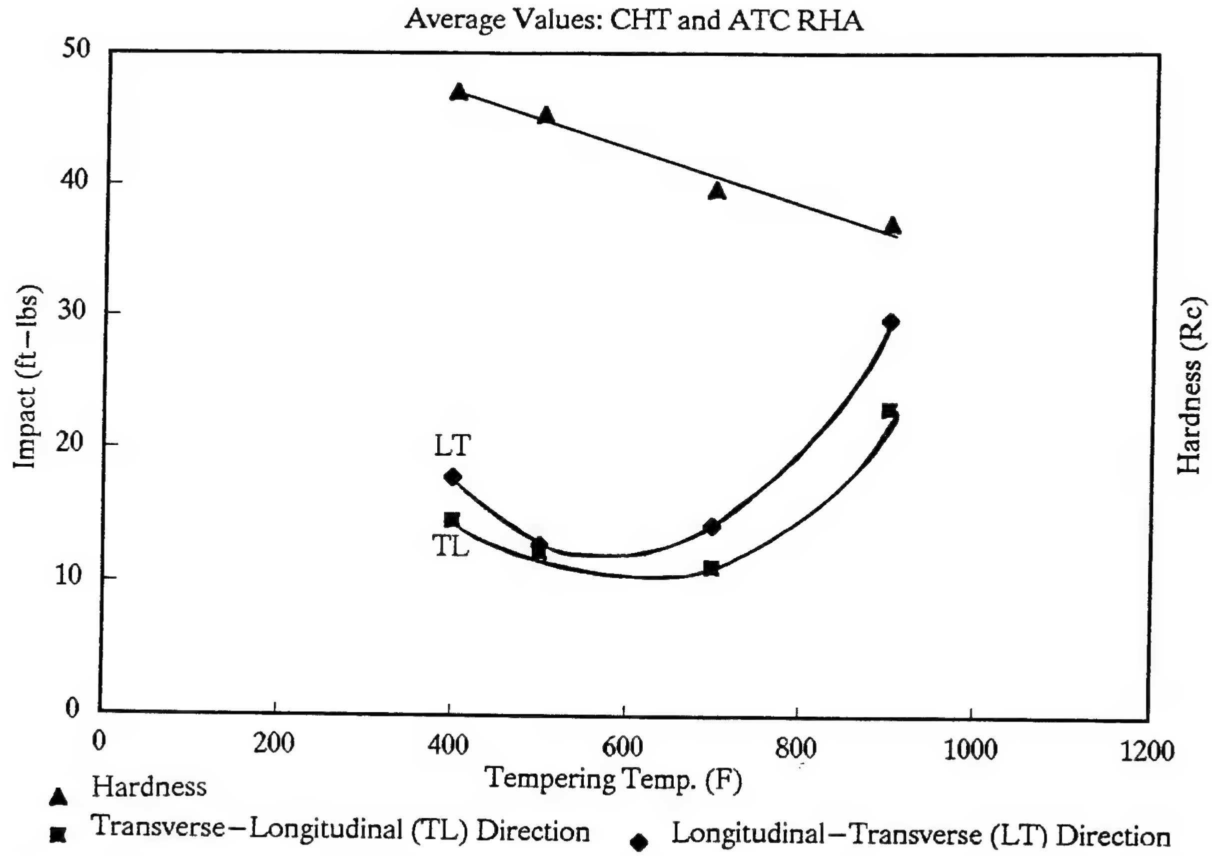


Figure 1. Charpy Impact and Hardness vs. Tempering Temperature for Mn-Mo-B RHA Steel.

Table 3. Ballistic Performance of Mn-Mo-B RHA Material Through Higher Hardness[a]

Test Projectile: 20-mm API M602

Tempering Temperature (°F)	Hardness Level (HRc)		V_{50} (ft/s)	
	CHT	ATC	CHT	ATC
275[b]	49.0	—	2,601	2,553
400	49.1	45.0	2,612	2,543
500	46.8	43.8	—	—
700	43.9	—	—	—
800	41.0	38.1	2,516	2,539
900	38.3	35.6	2,485	2,487

[a] Plate material, 1 1/2 in thick.

[b] As-quenched condition and stress-relieved tempered.

NOTE: 1 1/2-in-thick conventional RHA (HRc 33) tested to yield V_{50} = 2,404 ft/s.

Historically, hard steel and tungsten carbide alloys have been employed in armor piercing (AP) projectiles. However, during the 1980s, high-density, more ductile materials (namely depleted uranium [DU] and tungsten alloys) were introduced and are now prevalent in domestic and foreign ammunition, especially medium caliber (25 mm and 30 mm) and tank rounds (120 mm). Therefore, a set of ballistic experiments was designed to determine the performance of higher hardness or IRHA steel vs. a generic heavy metal penetrator. The penetrator selected was the standard laboratory quarter-scale rod (91% tungsten alloy with length-to-diameter ratio [L/D] = 10) weighing 65 g, shot at a nominal velocity of 4,900 ft/s at 0° obliquity. Performance was determined by penetration measurements as used in the depth-of-penetration (DOP) test for semi-infinite targets. Target arrays consisted of three RHA plates, each 1.5 in thick, clamped together for a total semi-infinite thickness of 4.5 in. Test results are shown in Figure 2, illustrating a linear effect of steel hardness on the reduction of rod penetration. For RHA steel hardened to HRc 48, approximately 25% reduction in penetration is achieved relative to conventional RHA at HRc 28. Post-mortem examination of the targets revealed symmetrical cavity shapes with very little of the penetrator remaining, indicative of the erosion defeat mechanism of heavy metal penetrators. It is important to note that this improvement in performance exhibited by the semi-infinite configuration should reasonably relate to the performance of an armor applique placed onto a substantial hull member. This is in contrast to finite armor targets, where the rear portion is allowed to deform and/or fails by petalling, shear plugging, spallation, cracking, or a combination of these failure modes.

The final test of an IRHA is to determine the candidate material's resistance to structural failure following severe, full-scale ballistic shock-loading. The test projectile employed is the 105-mm AP T182 round (Figure 3) consisting of a full-bore steel bullet weighing 35 lb, impacting at a nominal velocity of 3,000 ft/s. (This is equivalent to 5 million ft·lb of KE.) Full-scale test plates of the Mn-Mo-B alloy, measuring 36 in × 72 in × 1.5 in thick, were procured from and heat treated at CHT. Heat treatment included austenization at 1,650° F, rapid water quench, and tempering at 425° F to achieve HRc 48 throughout the plates. These plates were ballistically tested at Aberdeen Test Center (ATC) during the November–December 1990 time frame. Per acceptance shock-loading requirements, the plates were ballistically tested at 60° obliquity and −30° F and under ambient

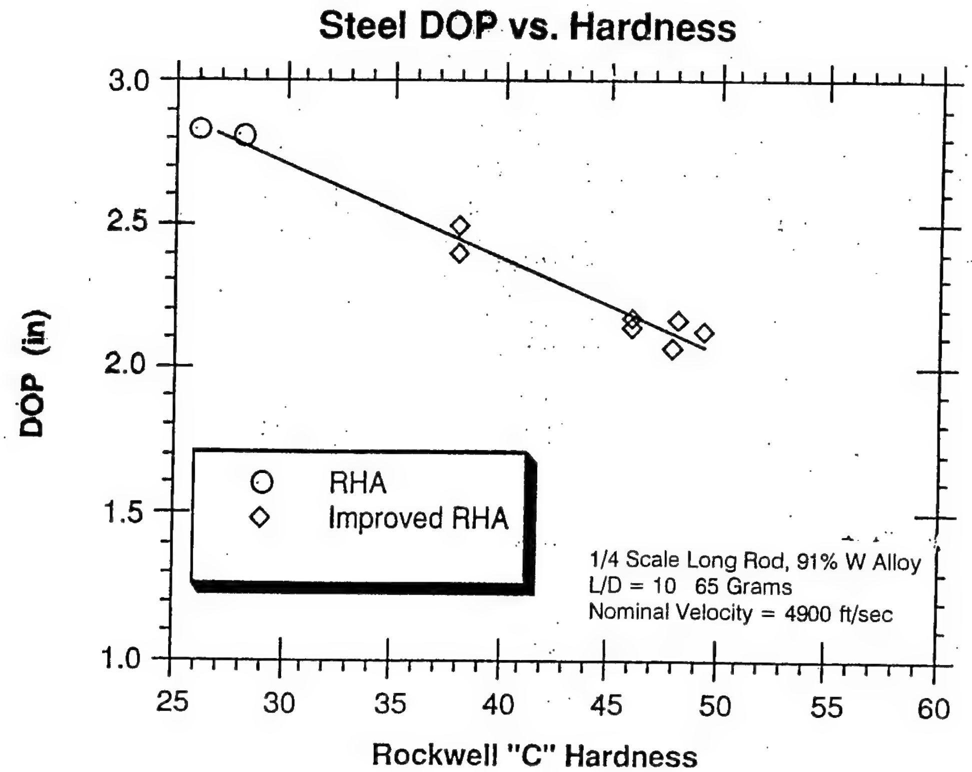


Figure 2. Steel DOP vs. Hardness.

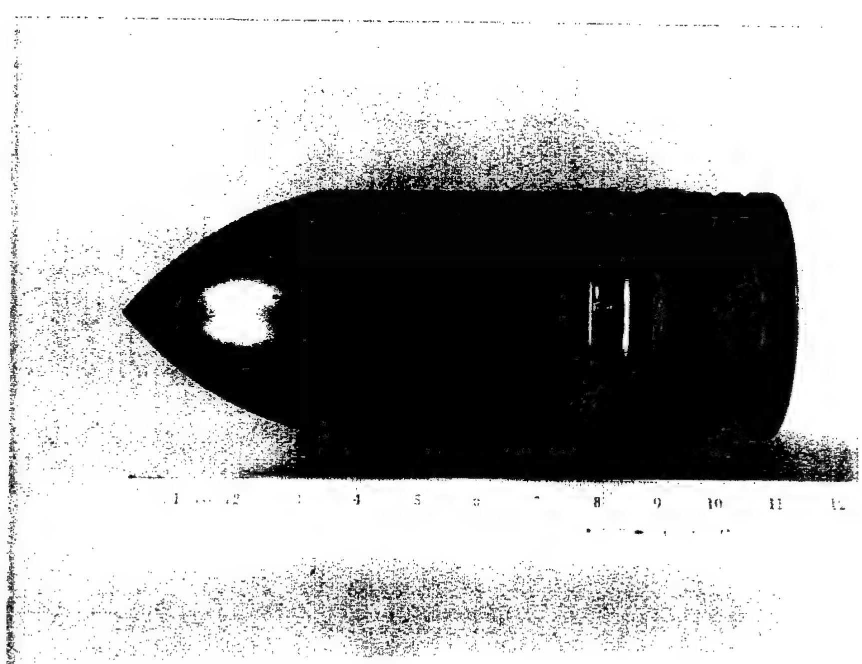


Figure 3. 105-mm AP T182 (35-lb Steel Bullet).

conditions (50° F–60° F). As illustrated in Figures 4 and 5, the plates failed the ballistic test requirement, due to excessive cracking and breakup. Plate failures were more catastrophic at the lower temperatures (−28° F) than at ambient temperatures (56° F). These ballistic shock-loading test results reaffirmed the CHV impact values (measured at −40° F) must be in excess of 20 ft·lb for a candidate structural armor material (Armor Design Handbook 1971). The mechanical properties for the full-scale test plates were identical to the values given in Table 1, namely CHV values of 18 ft·lb for the HRc 48 plate.

4. Ni-Cr-Mo RHA Alloy No. 1

4.1 Chemistry, Heat Treatment, and Metallurgical Analysis. To achieve the optimum combination of hardness and toughness, it became apparent that modification of the chemical composition of a generic RHA alloy, as well as variations in heat treatment, was required. Augmenting select alloying elements would be needed to achieve sufficient hardenability of the steel throughout the thickness range of interest. Hardenability of steel is defined as that property that determines the depth and distribution of hardness induced by quenching and is largely determined by the percentage of alloying elements (Grossman 1942). It should be noted that at this time (1991), the program scope was expanded to increase thicknesses into the 2-in–3-in range. Based on these factors and the previous test results with the Mn-Mo-B alloy, it was clear that the Ni-Cr-Mo RHA alloy system was best suited to achieve the goals of the program.

The chemical composition of the IRHA steel was developed by starting with an average chemical composition of the current Ni-Cr-Mo RHA and then optimizing this alloy by varying certain critical alloying elements. The primary objectives in developing the chemistry were to ensure a 98% or greater martensitic structure and a cross-sectional HRc 48 for armor plates that measure up to 3 in thick and could be produced using commercially accepted heat-treating and quenching practices. Furthermore, it was desired that toughness values in excess of 20 ft·lb (CHV values at −40° F) be maintained for all thicknesses and hardnesses. ARL-MD produced and processed in-house a number of 800-lb steel heats toward developing the improved chemistry. Steel heats were prepared

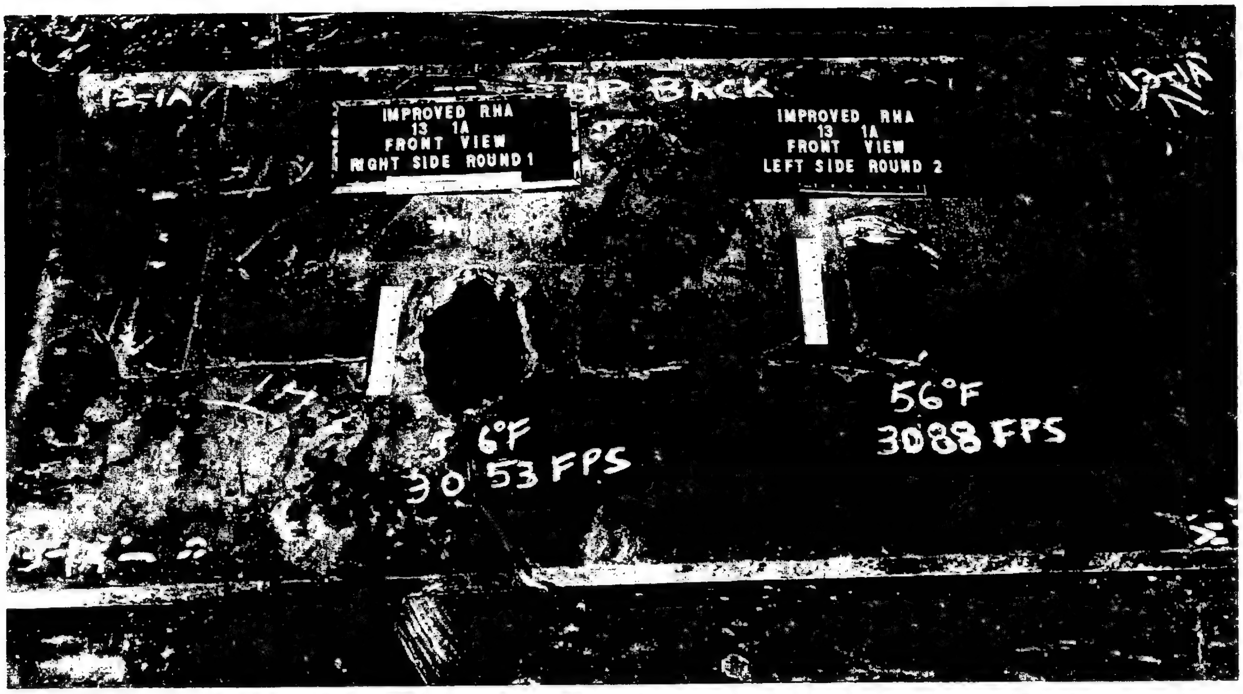


Figure 4. Higher Hardness Mn-Mo-B RHA Steel vs. 105-mm AP T182 Projectile.

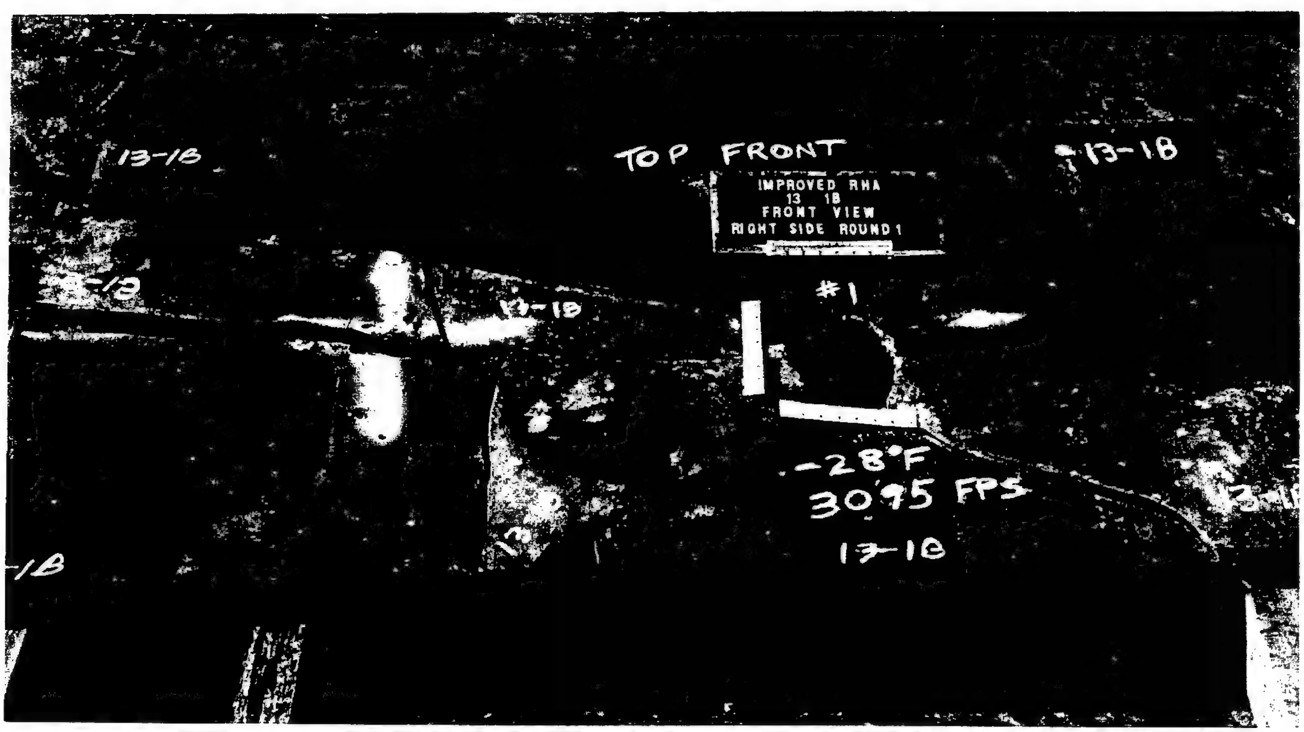


Figure 5. Higher Hardness Mn-Mo-B RHA Steel vs. 105-mm AP T182 Projectile.

by induction melting, cast into ingots that were refined by the electroslag refining (ESR) process, forged to slabs, rolled to thickness, and, finally, heat-treated to armor plates. Plates measuring 12 in × 12 in × 5/8 in to 1 1/2 in thick were obtained for ballistic testing and metallurgical analysis. To obtain larger plates for full-scale testing and evaluation and to validate commercial producibility, two heats (15 and 40 ton) were produced by Jessop Steel (Pittsburgh, PA) in concert with CHT. Material was ingot-cast at the Latrobe facility (Pittsburgh, PA), rolled to plate sizes at Jessop, and then heat treated at CHT (Ontario, Canada). Plates measuring 36 in × 72 in × 1 1/2 in and 2 1/2 in thick were produced and forwarded to ATC (APG, MD) for full-scale ballistic tests.

The interim IRHA chemistry developed and associated hardenability are outlined in Table 4. This chemistry employs relatively high Mn (1.1%) in concert with the traditional RHA alloying elements (Ni, Cr, and Mo) to ensure a high level of through-thickness hardenability: the hardenability being based on the resultant chemistry using critical ideal diameter (D_I) values. This D_I calculation method, developed by M. A. Grossman (1942), utilizes a series of hardenability factors for each alloying element in the composition. Using SAE J406 (Society of Automotive Engineers 1985), the calculated D_I hardenability was 11.3 for this interim IRHA chemistry. This value was confirmed experimentally by determining the hardenability using the Jominy Test Bar method according to ASTM A255 (American Society for Testing Materials 1995) that assesses hardenability based on cooling rates and hardnesses along the length of cylindrical Jominy bars machined from the IRHA plate. The D_I hardenability of 11.3 was considered more than adequate to obtain the required cross-sectional hardness and martensitic structure for plate thicknesses up to 3 in. Based on current industry water-quench cooling capability and practices, a minimum D_I of 8 is necessary to achieve this goal.

The hardness and Charpy impact values for the interim IRHA material (Jessop Heats No. 1 and No. 2) are shown in Figures 6 and 7 as a function of tempering temperature. It is important to note that CHV impact energies in excess of 30 ft·lb and HRc 48 were obtained for the material (Jessop Heats No. 1 and No. 2) tempered in the 400° F range. Furthermore, it should be noted that the Jessop Heat No. 2 material (Figure 7) follows the typical impact energy vs. tempering relationship

Table 4. Chemical Composition of Ni-Cr-Mo RHA Alloy No. 1

Source	C	Ni	Cr	Mo	Mn	Si	P	S	B
ARL-MD (In-House)	0.27	2.65	1.02	0.46	1.10	0.55	0.009	0.004	—
Jessop Heat No. 1	0.27	2.67	1.00	0.47	1.08	0.54	0.018	0.005	—
Jessop Heat No. 2	0.26	2.52	0.94	0.43	1.04	0.40	0.010	0.002	—

NOTE: Average Hardenability Index (D_I) = 11.3

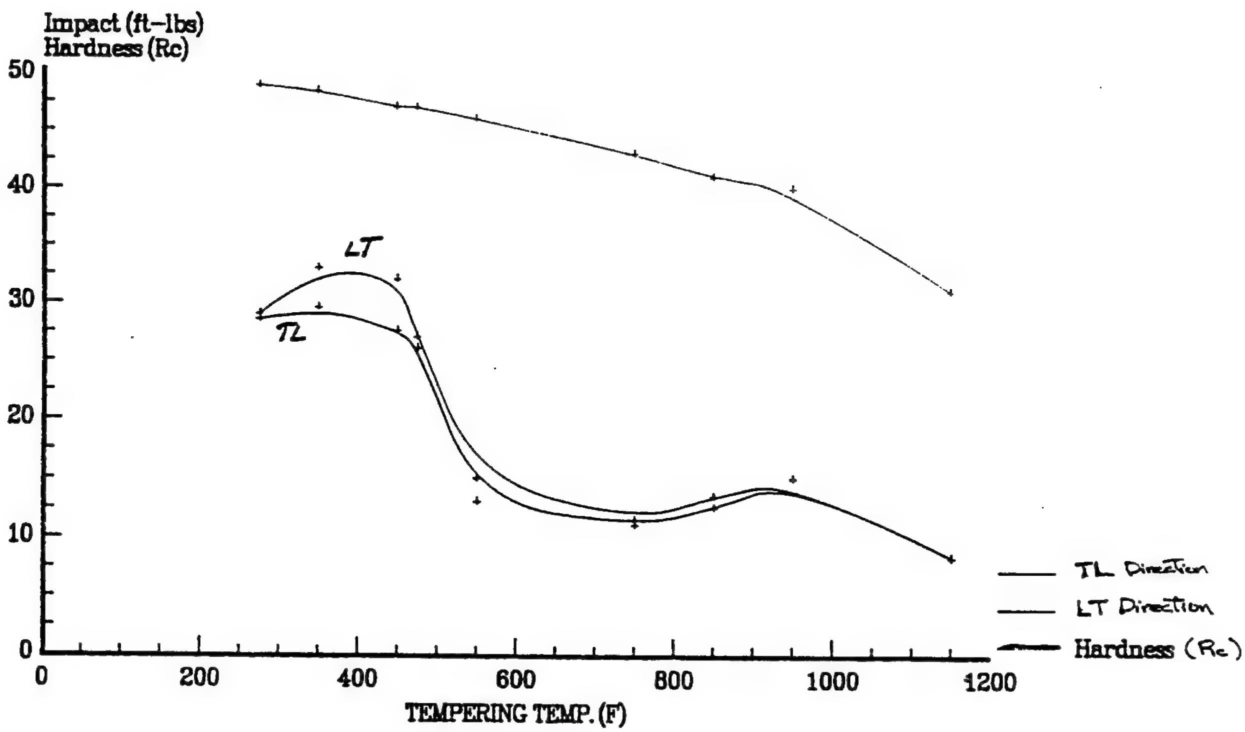


Figure 6. Charpy Impact and Hardness vs. Tempering Temperature for Ni-Cr-Mo Steel (Jessop Heat No. 1).

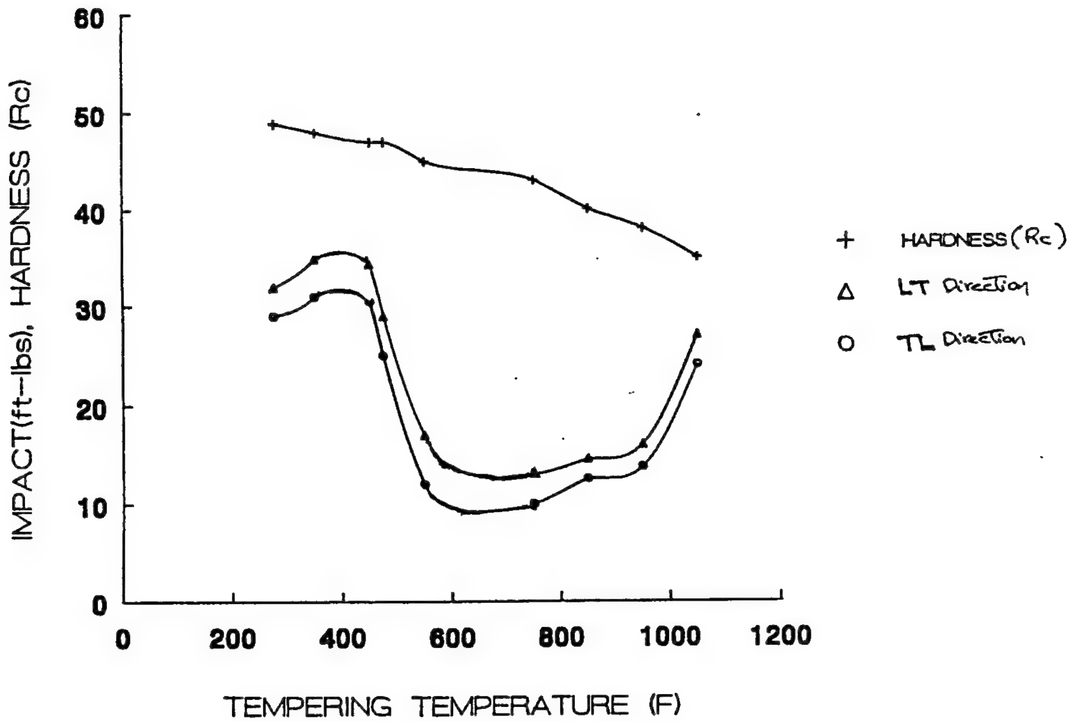


Figure 7. Charpy Impact and Hardness vs. Tempering Temperature for Ni-Cr-Mo Steel (Jessop Heat No. 2).

with an embrittlement region occurring between 450° and 800°, followed by recovery at the higher temperatures (>900° F). But for the Jessop Heat No. 1 material (Figure 6), the embrittlement region continues even at high tempering temperatures (1,150° F). This deleterious effort is attributed to the relatively high phosphorous impurity (0.018%) in combination with the high Mn alloying element.

The Jessop material (Heat No. 1) was further analyzed to confirm that basically 99% martensite is obtained under normal water-quench severity conditions. This was accomplished through a service contract (DAAL04-91-M-0492 Dr. R. Hanson) with Bethlehem Steel Corporation for development of a continuous-cooling-transformation (CCT) diagram and determination of volume percentages of the associated microstructures as a function of cooling rate. Table 5 provides these data, presented graphically in Figure 8 as the CCT diagram.

Table 5. Microstructures for Ni-Cr-Mo RHA Alloy No. 1 (Jessop Heat No. 1) as a Function of Cooling Rate

Sample Code	Cooling Rate[a] (°F/s)	Hardness (DPH-10 kg)	Volume Percentage		
			Pearlite	Bainite	Martensite
MTA10	46.7	482	0	0	100
MTA7	22.2	496	0	0	100
MTA5	2.2	478	0	0.8	99.2
MTA8	1.1	493	0	0.9	99.1
MTA11	0.82	477	0	2.0	98.0
MTA6	0.44	443	0	52.8	47.2
MTA4	0.22	440	0	69.2	30.8
MTA3	0.11	374	0	75.4	24.6
MTA9	0.05	362	0	100.0	0

[a] Cooling rate from 1,400° F to 1,200° F.

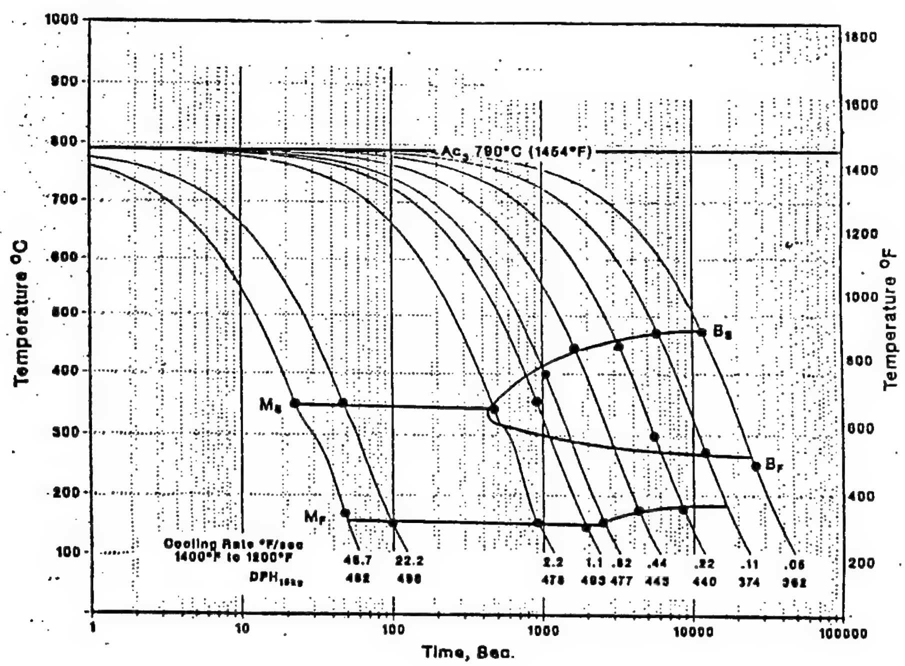


Figure 8. Continuous Cooling Transformation Diagram (Jessop Heat No. 1).

Photomicrographs shown in Figure 9 illustrate the martensitic microstructure for the various cooling rates. This interim, improved Ni-Cr-Mo (with high Mn) RHA material readily yields a 99% martensitic structure for cooling rates greater than 1.1° F/s. Water-quench rates exceed 4° F/s for existing steel mill facilities in the United States and Canada, assuring complete martensitic transformation with essentially no banite. This is illustrated by the CCT diagram with the banite start (B_s) and banite finish (B_f) curve minimum at the 2.2° F/s cooling rate. The importance of preventing the banite microstructure to ballistic performance cannot be overemphasized as shown by the empirical curves in Figure 10. Banite microstructures produce relatively brittle materials with low impact energies (CHV <15 ft·lb at −40° F) that crack or shatter upon ballistic loading.

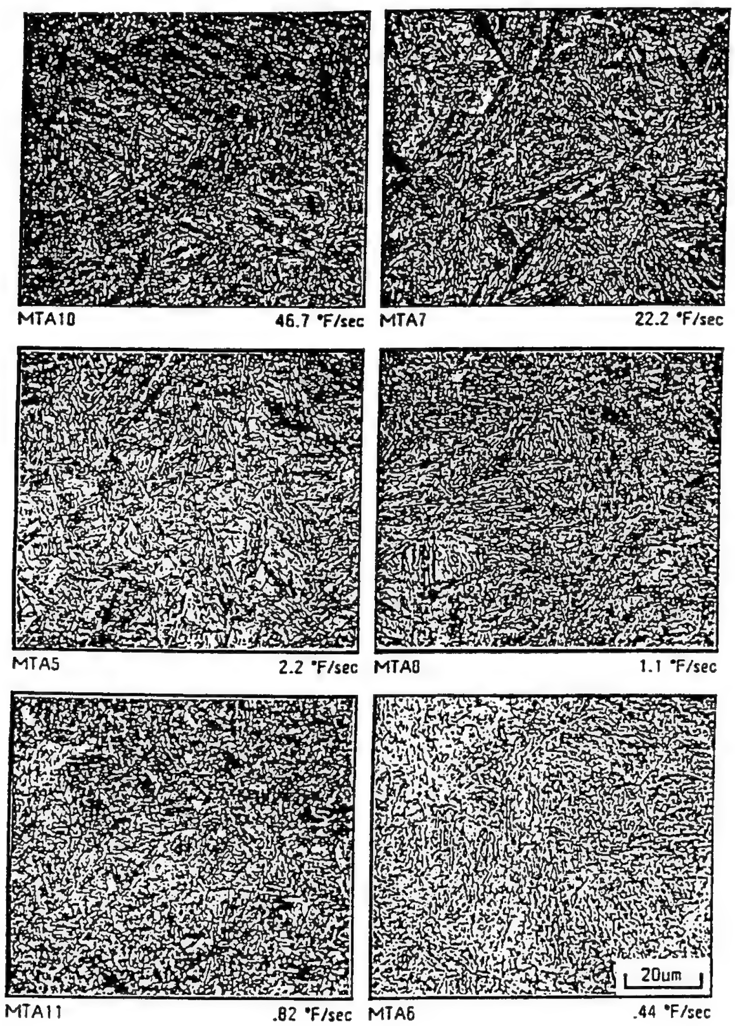


Figure 9. Photomicrographs for Ni-Cr-Mo RHA Alloy (Jessop Heat No. 1) Relating Microstructure to Cooling Rate.

4.2 Ballistic Test and Evaluation. Figure 10 also reiterates the importance of the tempered martensitic microstructure with CHV values in excess of 20 ft·lb (at −40° F) with respect to armor integrity upon ballistic loading. Full-scale ballistic tests with the 105-mm AP T182 proof projectile verified that the interim IRHA material (Jessop Heat No. 2 at HRc 48) could withstand high ballistic loading with little or no cracking. Test plates measuring 36 in × 72 in × 1 1/2 in and 2 1/2 in thick withstood two impacts (with minor or no cracks) at −30° F and 60° obliquity as shown in Figure 11.

The final full-scale ballistic tests were performed at ARL-WTD (APG, Maryland) employing a generic long-rod DU penetrator with an L/D ratio of 20. Armor configurations were assembled using 1 1/2-in and 2 1/2-in-thick IRHA plates in standardized tank test arrays previously tested using conventional RHA material. Test results (Table 6) revealed that the improved Ni-Cr-Mo RHA at the HRc 48 level performed no better than the standard RHA plate (HRc 28–33). The increase in penetrator erosion achieved by the higher hardness RHA was offset by premature shear plugging failure of the plates.

As expected, the ballistic performance of the IRHA at HRc 48 exceeded conventional RHA (HRc 33) vs. the standard 20-mm API M602 projectile used for acceptance testing. Test results given in Table 7 illustrate the greater ballistic enhancement achieved with higher hardness, especially for thicker gauge material.

5. Ni-Cr-Mo IRHA Alloy No. 2 - Optimal Material

5.1 Chemistry, Heat Treatment, and Metallurgical Analysis. Based on the previous test results, the program evolved toward a more traditional optimization of the Ni-Cr-Mo RHA alloy system. The optimization focused on increasing the Ni content with moderate increases in the Mo, Mn, and Cr alloying elements to achieve the proper level of hardenability while maintaining the carbon level at or below 0.27%. Furthermore, the alloying was adjusted to produce material that could be readily tempered to two hardness levels (HRc 48 and 40) that possessed high Charpy impact values. Following a series of 800-lb in-house heats, the optimal IRHA chemical composition was

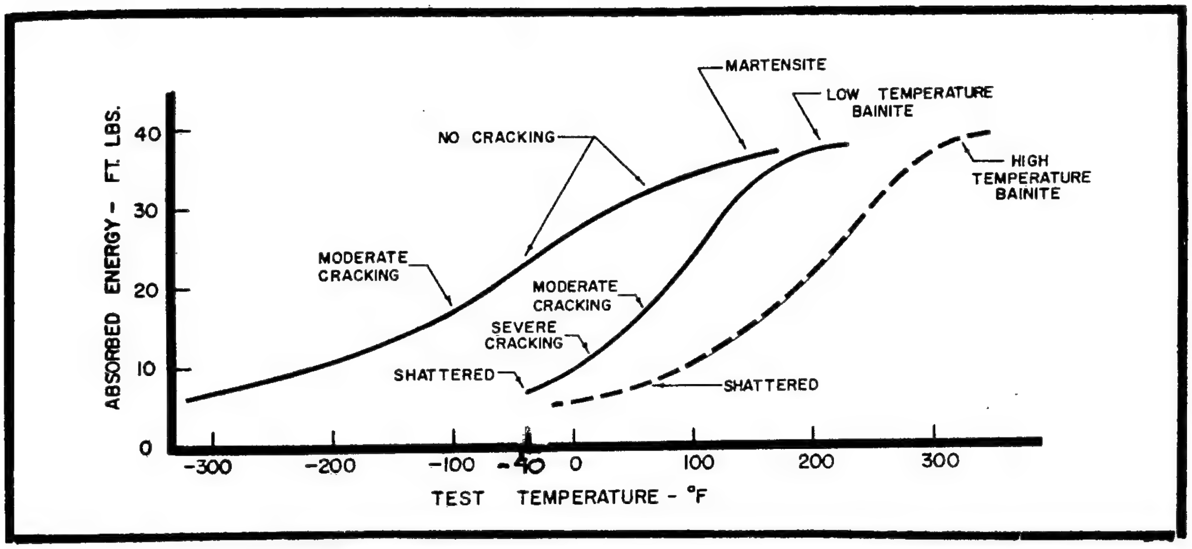


Figure 10. Correlation of Ballistic Shock Resistance Characteristics With CHV Bar Impact Properties at Various Temperatures.

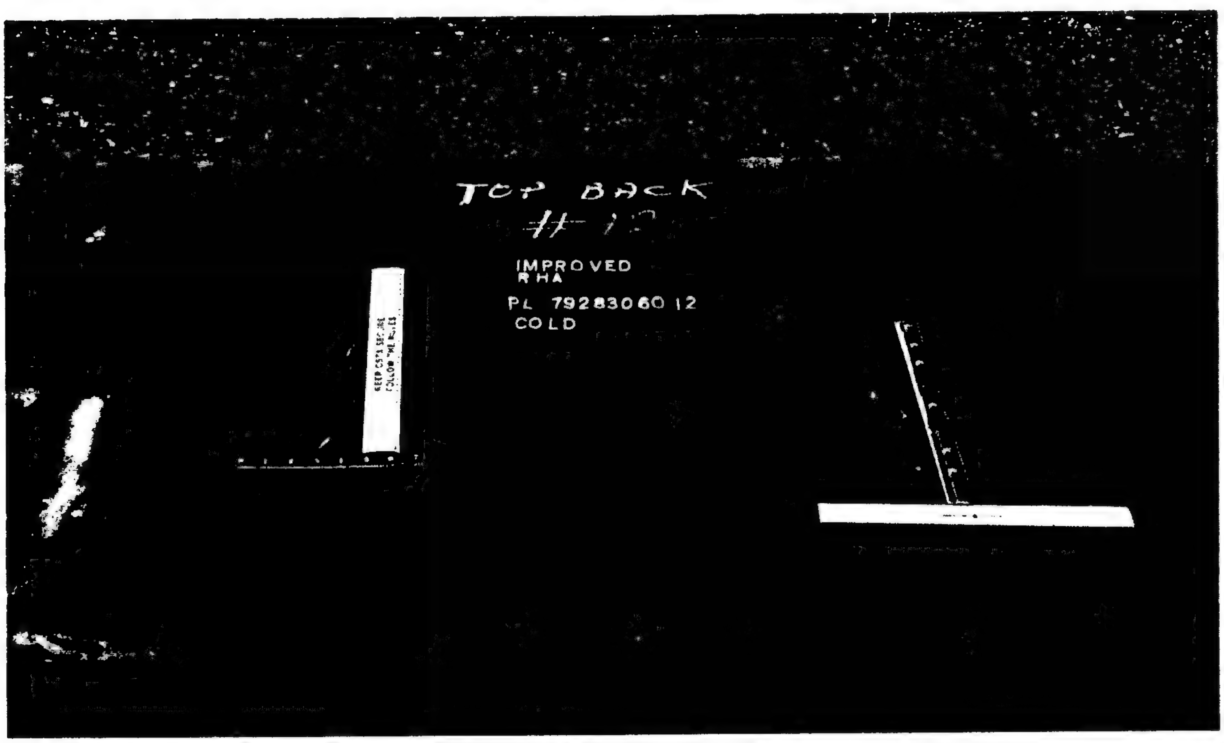


Figure 11. Steel Armor Plate Resistance to Ballistic Shock (Ni-Cr-Mo Alloy) vs. 105-mm AP T182 Projectile.

Table 6. Full-Scale Ballistic Test of IRHA[a] vs. Long-Rod Penetrator

Threat: Generic 120-mm long-rod penetrator, Series 3000, DU, L/D = 20

Target	Velocity (ft/s)	Result	Comments
IRHA (HRc 48): Series of 1 1/2-in and 2 1/2-in-thick plates in standardized configuration.	4,997	Complete Penetration[b]	Shear Plugging and Spalling of Plates
Conventional RHA (HRc 30): Series of 1 1/2-in and 2 1/2-in-thick RHA plates in standardized configuration.	4,675	Partial Penetration (Nearly Complete)	Large Deformation and Petal-Shear Plug Failure

[a] Ni-Cr-Mo Alloy (Jessop Heat No. 2), HRc 48
[b] 0.75-in Penetration into Witness Block

Table 7. Ballistic Performance of Ni-Cr-Mo IRHA Material[a] Through Higher Hardness

Plate Thickness	Hardness Level (HRc)	V_{50}(ft/s) 20-mm API M602	Percent Increase[b]
1.50 in	49.0	2,605	8.4
2.50 in	48.0	3,746	17.2

[a] Jessop Heat No. 2
[b] Percent Increase Relative to Conventional RHA: V_{50} (1.50-in-thick plate) = 2,404 ft/s; V_{50} (2.5-in-thick plate) = 3,195 ft/s.

finalized. As shown in Table 8, major features of the enhanced chemistry relative to conventional RHA is a 1% increase in Ni and small increases in Mo, Mn, and Cr. The increase in Ni ensured that ductility and toughness were not compromised, with Mn and Mo augmentation required to reach the desired level of hardenability. The carbon level was limited to 0.26% to ensure weldability comparable to standard RHA. The IRHA hardenability index (D_I) is in the 9–10 range compared to 3.5–5.5 for conventional RHA. A D_I value in the 9–10 range assures that the alloy will harden through the plate thickness (at least 3 in), irrespective of the water-quenching facility employed.

Table 8. Chemical Composition of Ni-Cr-Mo IRHA Alloy No. 2 - Optimal Material (Weight-Percent)

Source	C	Ni	Cr	Mo	Mn	Si	P	S	B	D_I
ARL-MD In-House (Heat No. 51B)	0.26	3.28	1.39	0.57	0.34	0.40	0.008	0.004	—	9.0
USS (200-ton Heat)	0.26	3.21	1.47	0.53	0.40	0.40	0.009	0.002	—	9.7
Average Hardenability Index (D_I) = 9.35										
Conventional MIL-A-12560 Average Chemistry	0.25	2.25	1.35	0.25	0.25	0.23	0.010	0.003	—	4.0

Figure 12 shows the Charpy impact and hardness values as a function of tempering temperature for the material obtained from the optimal in-house heat (51B). At least three Charpy specimens were machined from each temper; all specimens were in the transverse-longitudinal direction (the most severe condition). Note the Charpy impact energy of 22 ft·lb and HRc 48 obtained at the 425° F tempering temperature. More importantly, Charpy values of 30–40 ft·lbs were achieved for the 900°–1,000° F tempering range providing HRc 40 plates. Considering the wide breadth of ballistic threats, resistance to shock-load cracking, and weldability, the IRHA at the HRc 40 level provides the optimum properties.

Following completion of the optimal chemical composition, a full-scale, 200-ton heat was negotiated through the competitive bid process with subsequent award to USS (Gary Works, IN) via Contract No. DAAL04-91-C-0069. The USS heat employed the best full-scale steel mill production technology available. The 200-ton heat was melted in a basic oxygen process (BOP) furnace, vacuum degassed, and treated for sulfide shape control by the addition of calcium-silicon wire. Clean steel practice supplemented by argon stirring was utilized to minimize the entrapment of nonmetallic inclusions. The heat was cast into 12-in-thick slabs using a recently installed continuous caster that has supplanted the conventional ingot casting process. The 12-in-thick slabs were then rolled to the required thicknesses (3/4 in–2 1/2 in) and cut to size (nominal 72 in wide × 144 in long). The individual plates were heat treated in a continuous furnace with hold-down rolls in the water-

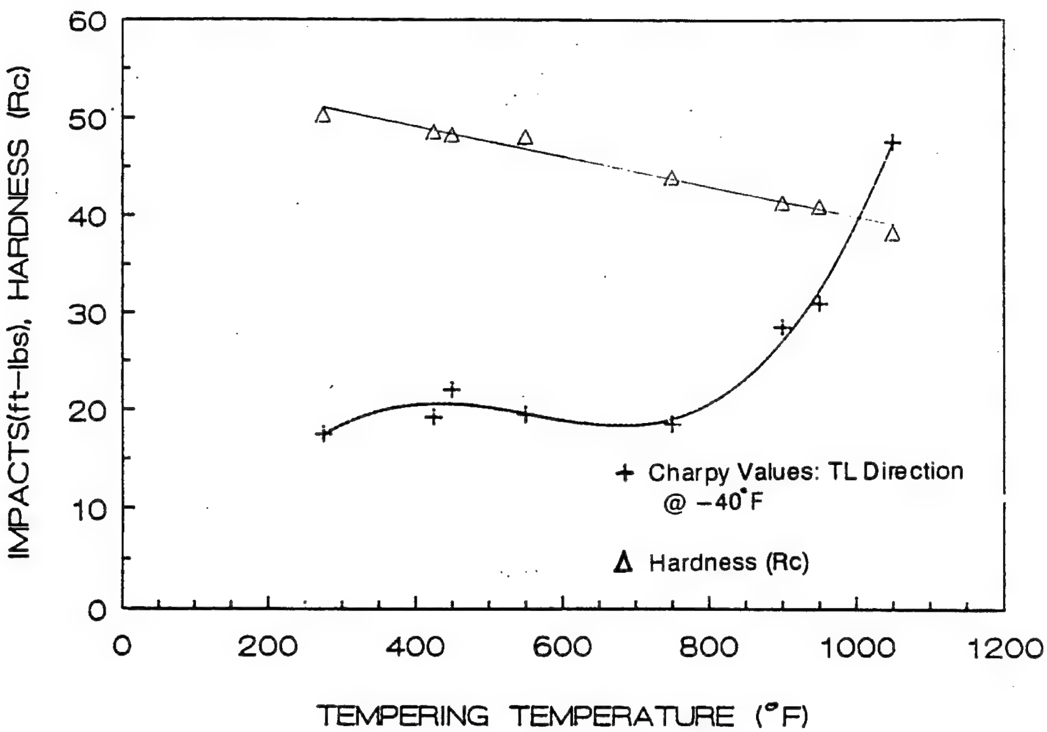


Figure 12. Charpy Impact and Hardness vs. Tempering Temperature for Heat 51B Ni-Cr-Mo Alloy Steel.

quench zone. Subsequent tempering was conducted in a continuous roller near the furnace. The chemistry for the USS heat was produced as specified in the contract and was nearly identical to the optimal in-house heat (Table 8).

The heat treatment of the plates consisted of austenitizing at 1,660° F, followed by water-quenching, and then tempering one lot of plates at 425° F to achieve nominal HRc 48 and the second lot of plates at 940° F to achieve HRc 40. Each lot contained plates of each thickness (3/4 in, 1 in, 1 1/4 in, 1 1/2 in, and 2 1/2 in). Plates were maintained at temperature approximately 1 1/2 hr per inch-thickness of plate (e.g., 250 m for a 2 1/2-in-thick plate).

Plates from USS heat were analyzed at ARL-MD (Watertown), and revealed that the Charpy impact values were appreciably below the values obtained for the in-house heat 51B. The major deviation occurred at the 940° F temper. Select plates were retempered at a higher temperature (985° F) at the USS facility, but yielded little or no increase in Charpy values (18–19.5 ft·lb). It was

important that the material have CHV values in excess of 20 ft·lb for structural integrity upon high ballistic loading.

An intense, in-house effort ensued to resolve the problem of relatively low CHV impact values for the 200-ton heat material. The first set of experiments reaffirmed that simply retempering at higher temperatures (985° F, 1,050° F, etc.) would not solve the problem, since undesirable complex carbide precipitates were present. Retempering would only increase the size of the complex carbide precipitates. Following a series of experiments, a resolution emerged consisting of the following actions: (1) normalizing at 1,700° F; (2) air cooling; (3) austenitizing at 1,625° F; (4) water-quenching; and (5) tempering at 985° F or 425° F, dependent on desired hardness (HRc 48 or 40, respectively). Normalizing is the critical step to ensure that any undesirable complex carbide precipitates present in the material are dissolved, and thereby achieve the optimum austenitic grain size. Using this five-step reheat treatment and laboratory-scale facilities at ARL-MD (Watertown), Charpy values (at −40° F) ranging from 27 to 30 ft·lb were obtained for the USS plate material at the 985° F temper, and 22 ft·lb at the 425° F temper. It was also confirmed that the dwell times at temperature, employed by USS for the initial heat-treatment cycle, were more than adequate. Figure 13 shows that the desired centerline temperature (measured by inserted thermocouples) is reached in only 60 min for a cold, 2 1/2-in-thick plate placed within a furnace slightly above the desired plate temperature (~100° F).

USS proceeded to reheat treat all the plates per the previously mentioned five-step schedule. Table 9 provides a summary of temperatures and times for each plate thickness. In addition, a 12-in-thick slab remaining from the primary 200-ton heat was rolled to size and similarly heat treated. This would provide material that was single heat treated, conforming to conventional practice. The single heat-treated plates are denoted by serial numbers 94982A and B (last entries in Table 9). Test specimens from the USS reheat-treated plates confirmed the improvement in toughness with CHV values of 24 and 21.5 (measured at −40° F) for the 985° F and 425° F tempers, respectively. The recovery in toughness is somewhat less than that achieved for the same material at ARL-MD (Watertown). This is not unusual considering the greater accuracy and control inherent with smaller

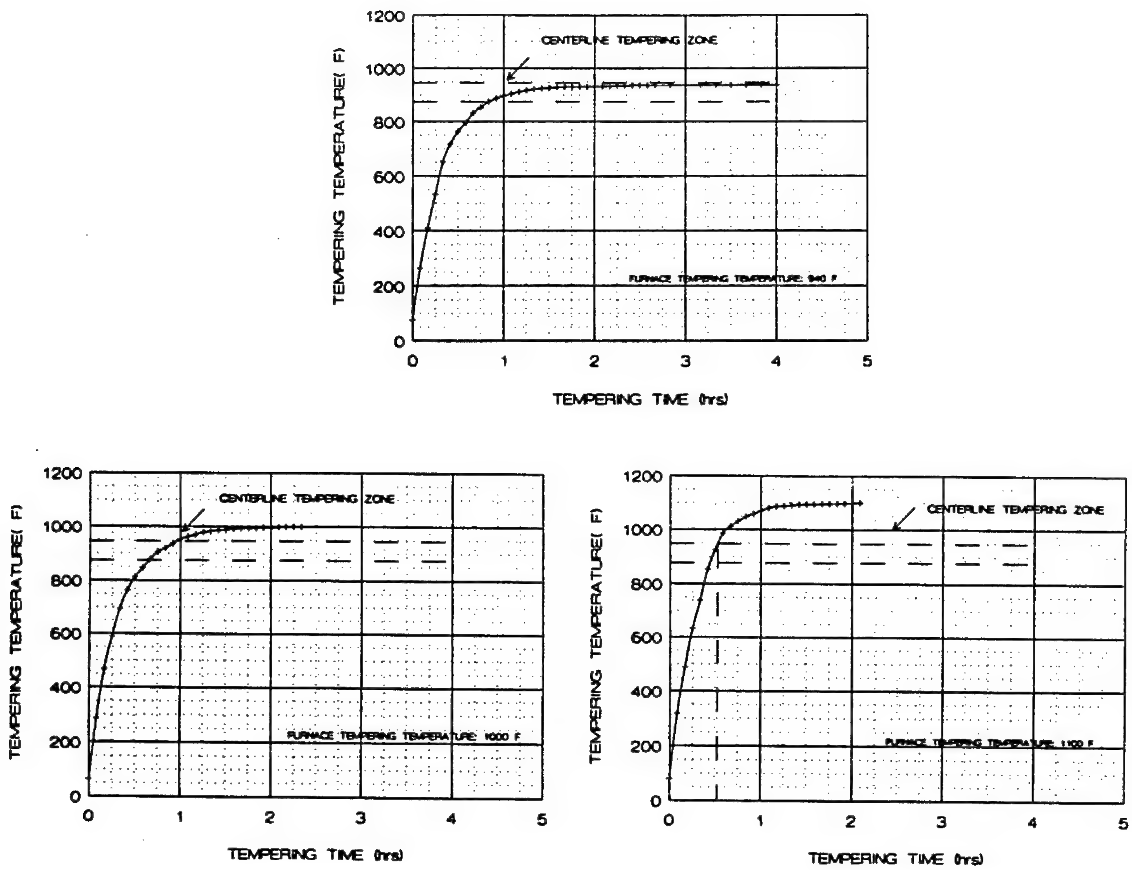


Figure 13. Centerline Temperature vs. Tempering Time for 2 1/2-in-Thick Steel Plates.

laboratory-scale equipment (heating furnaces, etc.) relative to large, full-scale steel mill facilities. Nevertheless, the goal of maintaining at least a 20-ft·lb Charpy impact was achieved. It was also encouraging that the single heat-treated material yielded results nearly identical to the reheat-treated plates. Test results for the 200-ton material following reheat treatment relative to the ARL-MD in-house results are summarized in Table 10. The mechanical properties for the reheat-treated plates are given in Table 11. The high levels of ultimate tensile strength, ratio of yield to tensile strength (YS/UTS), with reasonable elongation, for the two hardnesses (HRc 48 and 40) are indicative of high-quality steel armor plates. One should make a final note on the toughness and strength relationship of the IRHA USS plates relative to conventional RHA. The CHV values of 21–24 ft·lb

Table 9. USS Reheat Treatment of Armor Plate (Heat No. T43401; Contract No. DAAL04-91-C-0069)

Serial No.	Order No.	Size	Slab Cut	Normalize		Austenitize		Temper	
				Time (min)	Temp (°F)	Time (min)	Temp (°F)	Time (min)	Temp (°F)
97581B	LY18152-02	2 1/2 in × 72 in × 144 in	72-3	250	1,700	250	1,625	250	985
82071A	LY18153-01	2 1/2 in × 72 in × 144 in	74-2	250	1,700	250	1,625	250	425
97582A	LY18152-02	2 1/2 in × 72 in × 144 in	73-2	250	1,700	250	1,625	250	985
97582B	LY18152-02	2 1/2 in × 72 in × 144 in	73-2	250	1,700	250	1,625	250	985
97844A	LY18152-02	2 1/2 in × 72 in × 144 in	71-4	250	1,700	250	1,625	250	985
97843A	LY18152-02	2 1/2 in × 72 in × 144 in	71-3	250	1,700	250	1,625	250	985
97583COA	LY18151-01	2 1/2 in × 72 in × 72 in	73-1	250	1,700	250	1,625	250	425
97583COB	LY18151-01	2 1/2 in × 72 in × 72 in	73-1	250	1,700	250	1,625	250	425
97845BOA	LY18151-01	2 1/2 in × 72 in × 72 in	77-2	250	1,700	250	1,625	250	425
97845BOB	LY18151-01	2 1/2 in × 72 in × 72 in	77-2	250	1,700	250	1,625	250	425
97845AOA	LY18152-01	2 1/2 in × 72 in × 72 in	77-2	250	1,700	250	1,625	250	985
97845AOB	LY18152-01	2 1/2 in × 72 in × 72 in	77-2	250	1,700	250	1,625	250	985
97579A	LY18152-05	1 1/2 in × 72 in × 144 in	75-1	150	1,700	150	1,625	150	985
97579B	LY18152-05	1 1/2 in × 72 in × 144 in	75-1	150	1,700	150	1,625	150	985
97840A	LY18152-05	1 1/2 in × 72 in × 144 in	71-2	150	1,700	150	1,625	150	985

[a] Serials shipped at General Dynamics Land Systems (GDLS) (Lima, OH).

Table 9. USS Reheat Treatment of Armor Plate (Heat No. T43401; Contract No. DAAL04-91-C-0069) (continued)

Serial No.	Order No.	Size	Slab Cut	Normalize		Austenitize		Temper	
				Time (min)	Temp (°F)	Time (min)	Temp (°F)	Time (min)	Temp (°F)
97580C[a]	LY18150-05	1 1/2 in × 72 in × 144 in	73-3	150	1,700	150	1,625	150	985
97840C[a]	LY18150-05	1 1/2 in × 72 in × 144 in	71-2	150	1,700	150	1,625	150	985
97840B[a]	LY18150-05	1 1/2 in × 72 in × 144 in	71-2	150	1,700	150	1,625	150	985
97579D	LY18152-05	1 1/2 in × 72 in × 144 in	75-1	150	1,700	150	1,625	150	985
97580B	LY18151-04	1 1/2 in × 72 in × 144 in	73-3	150	1,700	150	1,625	150	425
97580A	LY18151-04	1 1/2 in × 72 in × 144 in	73-3	150	1,700	150	1,625	150	425
97841A	LY18151-04	1 1/2 in × 72 in × 144 in	74-1	150	1,700	150	1,625	150	425
97841B	LY18151-04	1 1/2 in × 72 in × 144 in	74-1	150	1,700	150	1,625	150	425
97576A	LY18153-02	1 1/4 in × 72 in × 144 in	75-3	125	1,700	125	1,625	125	425
97576B	LY18153-02	1 1/4 in × 72 in × 144 in	75-3	125	1,700	125	1,625	125	425
97574A	LY18152-08	1 1/4 in × 72 in × 144 in	76-3	125	1,700	125	1,625	125	985
97574B[a]	LY18150-08	1 1/4 in × 72 in × 144 in	76-3	125	1,700	125	1,625	125	985
97548A	LY18152-10	1 in × 72 in × 144 in	75-4	100	1,700	100	1,625	100	985
97548B	LY18152-10	1 in × 72 in × 144 in	75-4	100	1,700	100	1,625	100	985
97548C	LY18152-10	1 in × 72 in × 144 in	75-4	100	1,700	100	1,625	100	985

[a] Serials shipped at General Dynamics Land Systems (GDLS) (Lima, OH).

Table 9. USS Reheat Treatment of Armor Plate (Heat No. T43401; Contract No. DAAL04-91-C-0069) (continued)

Serial No.	Order No.	Size	Slab Cut	Normalize		Austenitize		Temper	
				Time (min)	Temp (°F)	Time (min)	Temp (°F)	Time (min)	Temp (°F)
97827A	LY18151-09	1 in × 72 in × 144 in	76-1	100	1,700	100	1,625	100	425
97827B	LY18151-09	1 in × 72 in × 144 in	76-1	100	1,700	100	1,625	100	425
97827C	LY18151-09	1 in × 72 in × 144 in	76-1	100	1,700	100	1,625	100	425
97546C	LY18151-11	3/4 in × 72 in × 144 in	72-1	75	1,700	75	1,625	75	425
97546D	LY18152-12	3/4 in × 72 in × 144 in	72-1	75	1,700	75	1,625	75	985
97546B	LY18152-12	3/4 in × 72 in × 144 in	72-1	75	1,700	75	1,625	75	985
97546A	LY18151-11	3/4 in × 72 in × 144 in	72-1	75	1,700	75	1,625	75	425
97547C	LY18151-11	3/4 in × 72 in × 144 in	72-2	75	1,700	75	1,625	75	425
97547B	LY18151-11	3/4 in × 72 in × 144 in	72-2	75	1,700	75	1,625	75	425
97547A	LY18152-12	3/4 in × 72 in × 144 in	72-2	75	1,700	75	1,625	75	985
97547D	LY18152-12	3/4 in × 72 in × 144 in	72-2	75	1,700	75	1,625	75	985
94982A[a]	LY18130-01	2 1/2 in × 72 in × 144 in	74-3	250	1,700	250	1,625	250	985
94982B	LY18131-02	2 1/2 in × 72 in × 144 in	74-3	250	1,700	250	1,625	250	425

[a] New serials rolled and heat treated as indicated. These were not part of the reheat treatment. Plates were normalized at 1,700° F, air cooled, austenitized at 1,625°, and water-quenched and tempered as indicated. Times at heat are noted for each temperature.

NOTE: All of the plates, except 94982A and 94982B, were reheat treated as follows: (1) Normalized at 1,700°, air cooled; (2) austenitized at 1,625°, water-quenched; and (3) tempered at either 425° or 985° as noted. Times at temperature are noted for each temperature.

Table 10. Effect of Reheat Treatment of USS 200-ton Heat Plates

Temper (°F)	CHV at −40° F[a] (ft·lb)		
	Baseline In-House Heat No. 51B	In-House Reheat Treatment of USS Material	USS Reheat Treatment of USS Material
425	21–22.5	22.0	21.5
985	30–32.5	27–30	24.0

[a] Charpy values in longitudinal-transverse (LT) direction.
NOTE: Charpy values ranged from 18.0 to 19.5 following initial heat treatment of 200-ton heat at USS.

Table 11. Mechanical Properties of Reheat-Treated USS 200-ton Heat Plates

Tempering Temperature (°F)	HRc	CHV Impact at −40° F (ft·lb)	0.2% YS[a] (psi)	UTS[a] (psi)	% Elongation	YS/UTS
425	47.5	21.5	189,000	240,000	14.4	0.79
925	40.5	24.0	168,000	190,000	17.2	0.88

[a] Values an average of five readings each in transverse and longitudinal directions using a 50K Instron machine.

are appreciably greater than the 16-ft·lb minimum requirement for conventional RHA at the HRc 42 level. (See Tables 4 and 5 within the current RHA specification, MIL-A-12560H.)

The USS material was further analyzed to confirm that the hardenability was adequate to achieve basically 99% martensite under conventional water-quench conditions. Bethlehem Steel, through an extended service contract (DAAL04-92-M-0452 Dr. R. Hanson), determined the percentages of martensite, retained austenite, and banite present as a function of water-cooling rates. Table 12 provides these data, which are presented as the CCT diagram in Figure 14. These data, and the photomicrographs in Figure 15, demonstrate that 99% martensite is obtained for cooling rates as low as 0.88° F/s, which is well within the normal water-quench severities of production steel mill facilities.

Table 12. Microstructures for Ni-Cr-Mo IRHA (USS 200-ton Heat) as a Function of Cooling Rate

Sample Code	Cooling[a] Rate (°F/s)	Hardness (DPH-10 kg)	Volume Percentage
MTD10	50	515	100% Martensite
MTD7	18	506	100% Martensite
MTD5	2.2	503	100% Martensite
MTD6	1.1	481	99% Martensite + 1% Retained Austenite
MTD8	0.88	498	99% Martensite + 1% Retained Austenite
MTD9	0.44	482	98% Martensite + Bainite, 2% Retained Austenite
MTD4	0.22	404	92% Martensite + Bainite, 8% Retained Austenite
MTD3	0.12	393	85% Martensite + Bainite, 15% Retained Austenite
MTD2	0.055	393	73% Martensite + Bainite, 27% Retained Austenite

[a] Cooling rate from 1,400° F to 1,200° F.

5.2 Ballistic Test and Evaluation. Ballistic V_{50} test results for the USS IRHA material (200-ton heat) vs. the conventional projectile threat requirements within MIL-A-12560 and the 20-mm fragment-simulating projectile (FSP) are summarized in Table 13. At both hardness levels (HRc 40 and 48), the IRHA outperforms standard RHA (from HRc 28 to 40-dependent on thickness). As expected, the higher hardness IRHA plate (HRc 48) is the best performer vs. the hard steel core 0.50-cal. APM2 projectile. However, against the relatively soft steel (HRc 30) chisel-nosed FSP, a dramatic reduction in performance occurs (670 ft/s) for the HRc 48 plate, due to the extensive shear plug failure mode of the material. Fortunately, the IRHA at the HRc 40 level maintains performance equal to or slightly better than the softer and more ductile conventional RHA vs. the critical FSP threat. Surprisingly, against the very hard and brittle tungsten carbide penetrator (20-mm API M602), the performance of the IRHA at both the HRc 40 and HRc 48 levels are comparable.

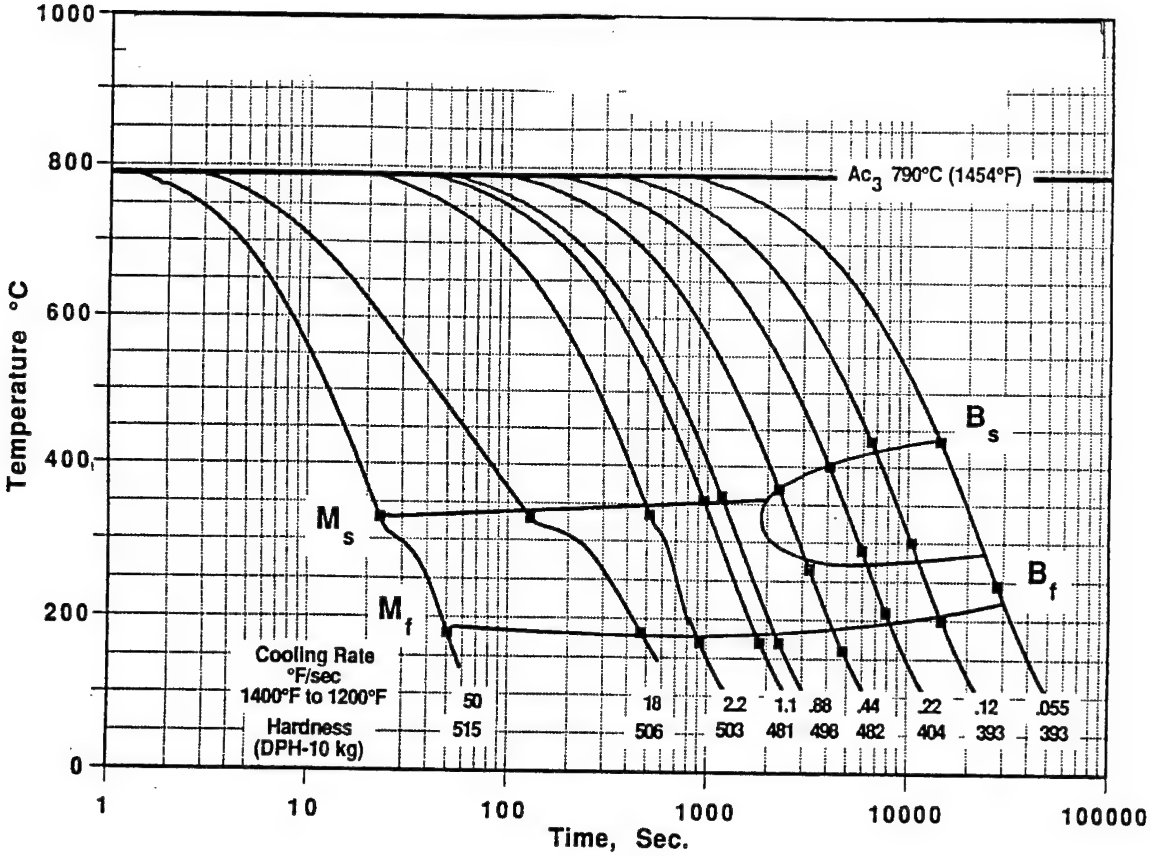


Figure 14. Continuous Cooling Transformation Diagram (USS 200-ton Heat).

As discussed earlier, full-scale shock-proof testing against the 105-mm AP T182 full-bore steel projectile is imperative for structural armor materials. IRHA at both hardnesses (HRc 40 and 48), measuring 36 in × 72 in × 1 1/4 in and 2 1/2 in thick were tested at ATC from January to March 1994. Test conditions were nominally at −30° F and ambient temperatures (56° F) with plate orientation at 60° obliquity (a worse condition for shock loading). All plates at both hardness levels passed the test firings consisting of two impacts per plate with negligible or minor cracking about the impact-penetration areas. Test results of firings are summarized in Table 14. These results confirmed that the IRHA could be employed similarly to conventional RHA as a structural armor withstanding high KE ballistic loading. Again, the correlation and criticality of the IRHA material processed to a tempered martensitic condition with Charpy impact values in excess of 20 ft·lb (at −40° F) was reaffirmed (Figure 10).

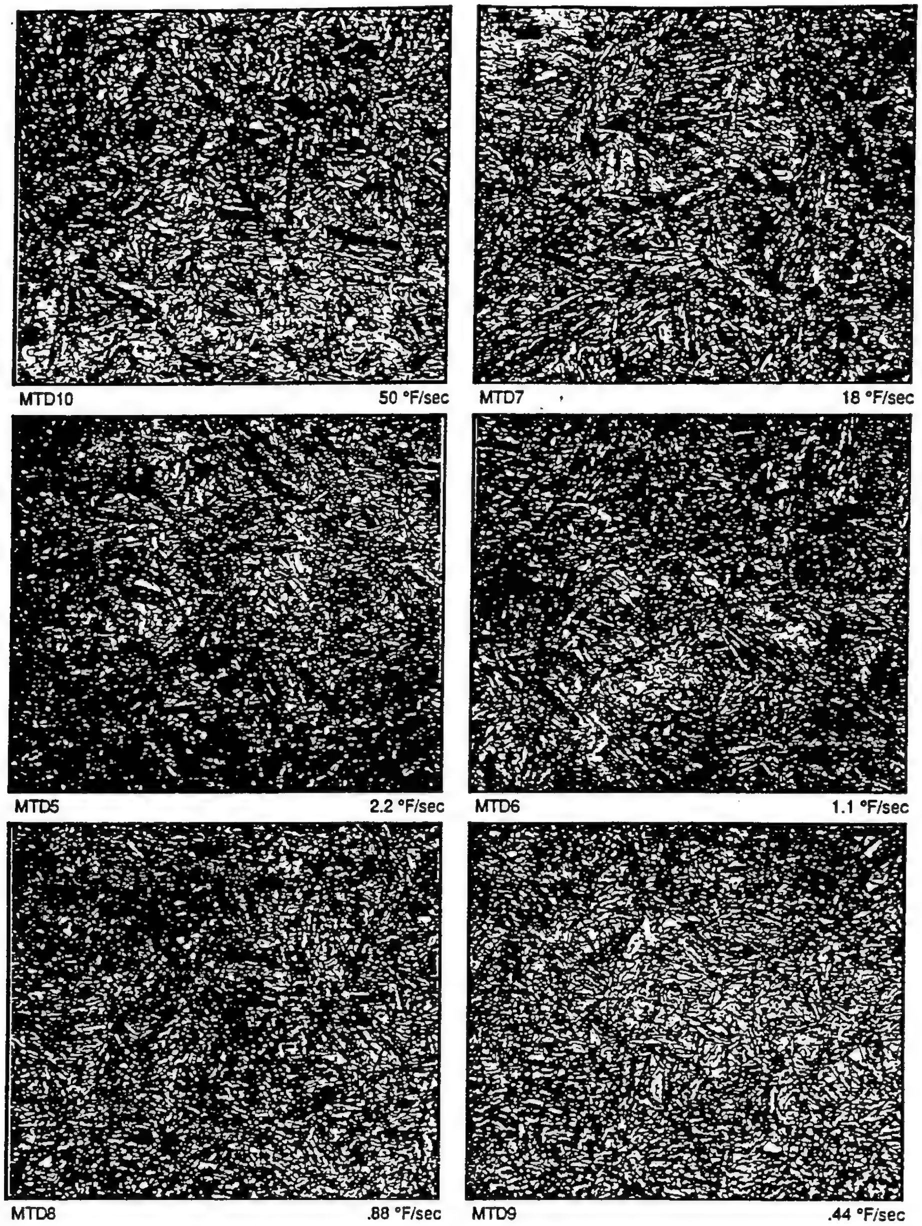


Figure 15. Photomicrographs for Ni-Cr-Mo IRHA Alloy (USS Heat) Relating Microstructure to Cooling Rate.

The next series of full-scale ballistic tests focused on performance of the IRHA material against a generic tank heavy metal penetrator. Tests were performed at and under direction of ARL-Weapons Technology Directorate (WTD). The test penetrator chosen, based on previous efforts at WTD and cost considerations, was a segment of a long-rod penetrator with an L/D of 5, 93%

Table 13. Ballistic Performance of IRHA vs. Conventional Projectiles (USS 200-ton Heat)

Thickness (in)	Hardness Level (HRc)	Projectile	V_{50} (ft/s)	V_{50} (ft/s)[a]	Excess (ft/s)
0.755	41.0	0.50-cal. APM2	2,378	2,288	90
0.752	48.0	0.50-cal. APM2	2,501	2,284	217
1.000	40.5	0.50-cal. APM2	2,803	2,680	123
1.007	48.0	0.50-cal. APM2	3,094	2,690	404
0.992	40.5	20-mm FSP	4,198	4,100	98
1.002	48.0	20-mm FSP	3,430	4,100	(−670)
1.258	40.5	20-mm API M602	2,217	2,115	102
1.256	48.0	20-mm API M602	2,118	2,113	5
1.500	40.5	20-mm API M602	2,614	2,364	250
1.504	47.5	20-mm API M602	2,600	2,368	232
2.500	40.5	20-mm API M602	3,624	3,182	442
2.502	47.5	20-mm API M602	3,749	3,183	566

[a] MIL-A-12560.

tungsten alloy material, weighing 555 g. Both semi-infinite and finite target configurations were tested using 2 1/2-in-thick IRHA plates of both hardness levels (HRc 40 and 48) as shown in Figure 16; all tests were performed at 30° obliquity. The conventional line-of-sight (LOS) penetration measurement was used to quantify performance. For the semi-infinite target configuration, test results are presented graphically in Figure 17. Relative to standard RHA (HRc 34), approximately 22% and 15% less penetration is allowed by the IRHA at the HRc 48 and HRc 40 levels, respectively. This is expected since the harder IRHA is more efficient in eroding the relatively softer tungsten penetrator material. This improvement in performance or reduction in penetration is consistent with previous data presented in Figure 2 vs. the 1/4 scale, L/D = 10, 65-g tungsten penetrator. Again, it should be emphasized that the semi-infinite configuration test results

Table 14. Full-Scale Ballistic Shock-Loading Tests (IRHA, 200-ton Heat Plates)

Test Projectile: 105-mm AP T182, 60° Obliquity

Date	Shot No.	Plate Serial No.	Nominal Thickness (in)	Hardness Level (HRc)	Striking Velocity (ft/s)	Test Temp (°F)	Hole Dimensions (in)[a]	
							Major Axis	Minor Axis
5 Jan 94	1	97576B	1.250	48	3,025	−28	10.24	6.69
5 Jan 94	2	97576B	1.250	48	3,035	−20	10.24	4.72
6 Jan 94	3	82071A	2.500	48	3,041	−47	7.87	5.51
6 Jan 94	4	82071A	2.500	48	3,041	−40	8.27	5.51
6 Jan 94	5	82071A	2.500	48	3,051	−44	7.48	5.12
6 Jan 94	6	82071A	2.500	48	3,064	−40	8.27	5.12
10 Jan 94	7	97574A	1.250	40	3,015	−40	11.42	4.72
10 Jan 94	8	97574A	1.250	40	3,015	−25	9.25	5.31
10 Jan 94	9	97845AOA	2.500	40	3,041	58	7.87	5.12
10 Jan 94	10	97845AOA	2.500	40	3,048	46	7.09	5.12
13 Jan 94	11	97581B	2.500	40	3,058	−45	6.30	5.91
13 Jan 94	12	97581B	2.500	40	3,025	−36	9.84	7.87
13 Jan 94	13	97581B	2.500	40	3,035	−40	6.89	5.51
13 Jan 94	14	97581B	2.500	40	3,045	−35	8.27	5.51
13 Jan 94	15	97574A	1.250	40	3,032	−41	5.31	5.12
13 Jan 94	16	97574A	1.250	40	3,028	−31	9.65	5.12
14 Jan 94	17	97574A	1.250	40	Lost	−40	9.06	4.72
14 Jan 94	18	97574A	1.250	40	3,035	−31	9.45	5.51
7 Mar 94	19	94982B	2.500	48	3,064	55	9.45	5.51
7 Mar 94	20	94982B	2.500	48	3,061	55	6.69	5.51

[a] All plates passed the "resistance to cracking" requirement.

Table 14. Full-Scale Ballistic Shock-Loading Tests (IRHA, 200-ton Heat Plates) (continued)

Date	Shot No.	Plate Serial No.	Nominal Thickness (in)	Hardness Level (HRc)	Striking Velocity (ft/s)	Test Temp (°F)	Hole Dimensions (in)[a]	
							Major Axis	Minor Axis
8 Mar 94	21	94982A	2.500	40	3,048	-37	8.27	4.33
8 Mar 94	22	94982A	2.500	40	3,061	-9	7.09	4.72
8 Mar 94	23	97576B	1.250	48	3,058	-40	9.25	4.53
8 Mar 94	24	97576B	1.250	48	3,055	-15	9.45	5.12

[a] All plates passed the "resistance to cracking" requirement.

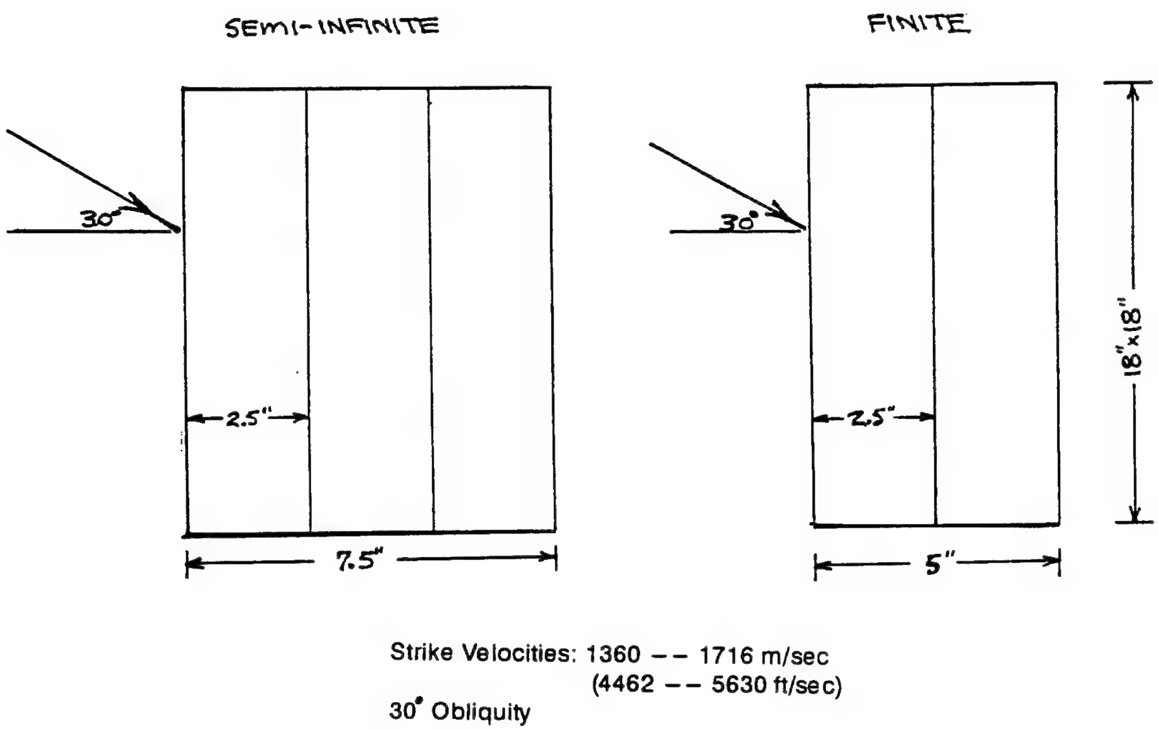


Figure 16. Full-Scale Armor Configurations vs. L/D = 5 (555-g Penetrator).

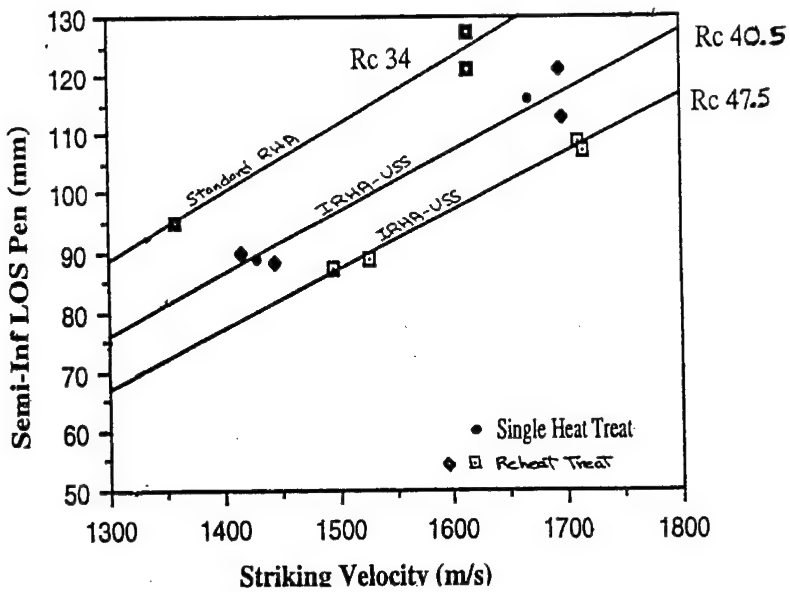


Figure 17. Penetration vs. Velocity for IRHA Full-Scale Semi-Infinite Armor Configuration.

are indicative of the performance of an applique armor placed onto a substantial hull with negligible rear section response.

For the finite target configuration, the test results are provided in Table 15. Test results similar to the semi-infinite targets were obtained with reduction in penetrations of 22% and 12% for the HRc 48 and HRc 40 IRHA material relative to standard RHA. Examination of data revealed that penetration holes ended 25 mm to 35 mm from the rear face of the targets, thereby rendering performance similar to a semi-infinite configuration.

6. Weldability and H-Plate Testing

Investigation of weldability and ballistic impact tolerance of a typical welded structure for the IRHA material was performed by General Dynamics Land Systems (GDLS) (1996) under ARL-MD Contract No. DAAL04-91-C-0040. The objective was to determine if the IRHA material was

Table 15. Ballistic Test of an IRHA Full-Scale Finite Armor Configuration

Penetrator: L/D = 5 (555 g, tungsten alloy, 105 mm)
Obliquity = 30°

Material	Thickness (in)	Hardness Level (HRc)	Strike Velocity (m/s)	Result[a]	Penetration (mm)
IRHA-USS	2.5 + 2.5	47.5 + 40.5	1,645 1,728	PP PP	111.89 121.63
IRHA-USS	2.5 + 2.5	47.5 + 47.5	1,664 1,690	PP PP	100.00 106.00
Standard RHA[b]	2.5 + 2.5	34 + 34	1,662	PP	129.51

[a] PP = Partial Penetration
[b] MIL-A-12560G

amenable to processing by methods employed for constructing the M1 Abrams tank at the General Dynamics Tank Plant at Lima, OH (LATP).

The weldability evaluation was conducted on both the HRc 40 and HRc 48 material, but with greater emphasis devoted to the HRc 40 material. A Y-groove joint method, as adopted by GDLS, was used to determine the proper preheat temperature prior to welding. Preheat temperatures of 200°, 250°, 275°, 300°, and 400° F were used for the 1 1/2-in and 2 1/2-in-thick material. Following a 72-hr incubation period, the weld joint was removed by flame cutting and the edges were ground. Test coupons were sectioned, metallographically prepared, and microscopically examined. No heat-affected zone (HAZ) cracking occurred on sections preheated at 275° and above. HAZ cracking was exhibited on samples at 200° F and, on one of the five samples, at 250° F. It was mutually agreed between ARL-MD and GDLS that a minimum preheat and interpass temperature of 300° F would be maintained to ensure high-integrity weldments.

One H-plate was fabricated with the standard 1 1/2-in RHA steel: Three different approved welding processes at the LATP were used to fabricate the IRHA H-plates:

RHA H-Plate 74: HCD.

Three H-plate weldments were fabricated at the LATP using the USS 1 1/2-in-thick HRc 40 material.

IRHA H-Plate 106: High Current Density (HCD),

IRHA H-Plate 107: Gas Metal Arc Welding (GMAW) Spray Transfer, and

IRHA H-Plate 108: Gas Metal Arc Welding (GMAW) Spray Transfer.

All three welding processes are employed on various sections of Abrams tank fabrication. The RHA H-plate (74) was welded using the HCD welding process, with the same parameters as H-plate 106. The three IRHA H-plates were fabricated maintaining a 300° preheat and interpass temperature, while the RHA H-plate maintained a 200° F preheat and interpass temperature that is conventionally used for tank fabrication. The welding data sheet for H-plate 106, giving the welding parameters and weldment sequence, is provided in Figure 18. The four H-plates were x-ray-examined to ASTM Grade 2 and shipped to ATC for ballistic shock-proof testing.

ATC performed ballistic shock tests on the four H-plates per MIL-STD-1941 (MR). H-plates were impacted at the weldments with the 75-mm M1002 proof projectile at or above the required velocity of 1,194 ft/s and then visually and radiographically examined. All H-plates passed the maximum allowable weld-cracking requirement following ballistics impact as outlined in MIL-STD-1941 (MR). Table 16 provides the test results, and Figure 19 illustrates the resistance to cracking for a typical IRHA H-plate (plate No. 106).

Thermal cutting and machinability experiments were also performed on the IRHA material (HRc 40 and 48). Both plasma and oxy-fuel cutting of 1 1/2-in-thick test plates were performed with no defects or indications observed in the cut edges using macro and microscopic metallographic nondestructive (NDT) machining methods. Machining operations included milling, drilling, tapping, boring, and reaming. The same tooling and parameters were used as on conventional RHA at the LATP. All the machining operations performed satisfactorily for the IRHA with no notable

FORM 1

WELD ARMOR DATA

REPORT NO:
SHEET __ OF __

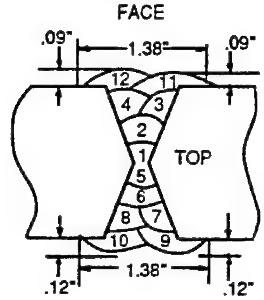
PLATE NO: 106	SUBMITTED BY: GENERAL DYNAMICS
DATE: FEBRUARY 25, 1994	LAND SYSTEMS DIVISION
TYPE: 3	1161 BUCKEYE ROAD
THICKNESS: 1.5"	LIMA, OHIO 45804
SPECIFICATION: MIL-A-12560G	CONTRACT NO: DAAL04-91-C-0040

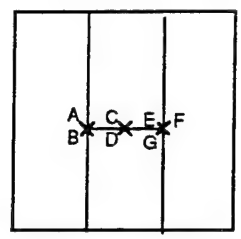
ORDNANCE MATERIAL CONCERNED: I-RHA ARMOR - USS

WELDED BY: ED JOHNSON

OBJECT: BALLISTIC SHOCK TEST

On a dimensional sketch of the groove and weldment, indicate: (1) the included angle; (2) the root opening; (3) the root face; (4) the bead sequence; (5) additional sketch of spacer strip on back-up, if any: (6) width of masking, if any, on edges of plate; (7) average height of reinforcement.





CROSS-BAR

Weld reinforcement ~~(has)~~ (has not) been removed.

WELDING DATA

NOZZLE COATING: NONE	JOINT COATING: NONE
PLATE PREPARATION: GRIND	BACKING TAPE: 45 CERAMIC
POSITION OF WELDING FLAT	SHIELDING GAS: 95%AR - 5%OX
WELDING: G.M.A.W. SEMI-AUTOMATIC (H.C.D.)	
PREHEAT: 300 F MINIMUM	POSTHEAT: NONE
PEENING: NONE	BUTTERING: NONE

	PASS	ELEC SIZE	TYPE PASS	CLEAN	AMPS	VOLT	WIRE SPEED	WELD LENGTH	INTERPASS TEMP (°F)		
									A-B	C-D	E-F-G
	1	.045	S	WB	320	27.0	450	10.00" / 0:47	305	305	305
	2	.045	S	WB	330	28.0	450	11.25" / 1:13	315	315	315
	3	.045	S	WB	340	28.0	450	11.75" / 0:48	310	310	310
BACKGRIND	4	.045	S	WB	340	28.0	450	11.75" / 0:52	305	310	305
	5	.045	S	BG	310	27.0	450	10.00" / 0:55	305	305	305
	6	.045	S	WB	340	28.0	450	11.25" / 1:10	300	300	300
	7	.045	S	WB	330	28.0	450	11.25" / 0:46	300	305	300
	8	.045	S	WB	340	28.0	450	11.25" / 0:53	305	310	305
	9	.045	S	WB	450	36.5	800	11.75" / 0:50	310	315	310
	10	.045	S	WB	440	36.5	800	11.50" / 0:42	300	305	300
	11	.045	S	WB	470	36.5	800	12.50" / 0:55	305	310	305
	12	.045	S	WB	340	28.0	450	12.75" / 1:00	310	315	310
	13										
	14										

S=Stringer Bead W=Weave Pass WB=Wire Brush BG=Background

Figure 18. Welding Data Sheet for H-Plate Weldment (USS IRHA).

Table 16. Ballistic Test of Welded H-Plates[a]

Material	Plate No.	Thickness (in)	ATC Firing Record No.	Required Velocity (ft/s)	Actual Velocity (ft/s)	Total Weld Cracking (in)	Pass/Fail[b]
IRHA[c]	106	1.494	940670	1,194	1,210	5 1/8	Pass
IRHA[c]	107	1.499	940671	1,200	1,205	None	Pass
IRHA[c] (Shot 1)	108	1.491	940672	1,194	1,204	1 1/2	Pass
IRHA[c] (Shot 2)	108	1.491	940672	1,194	1,206	9 1/2	Pass
RHA[d] (Conventional)	74	1.490	940669	1,194	1,204	1	Pass

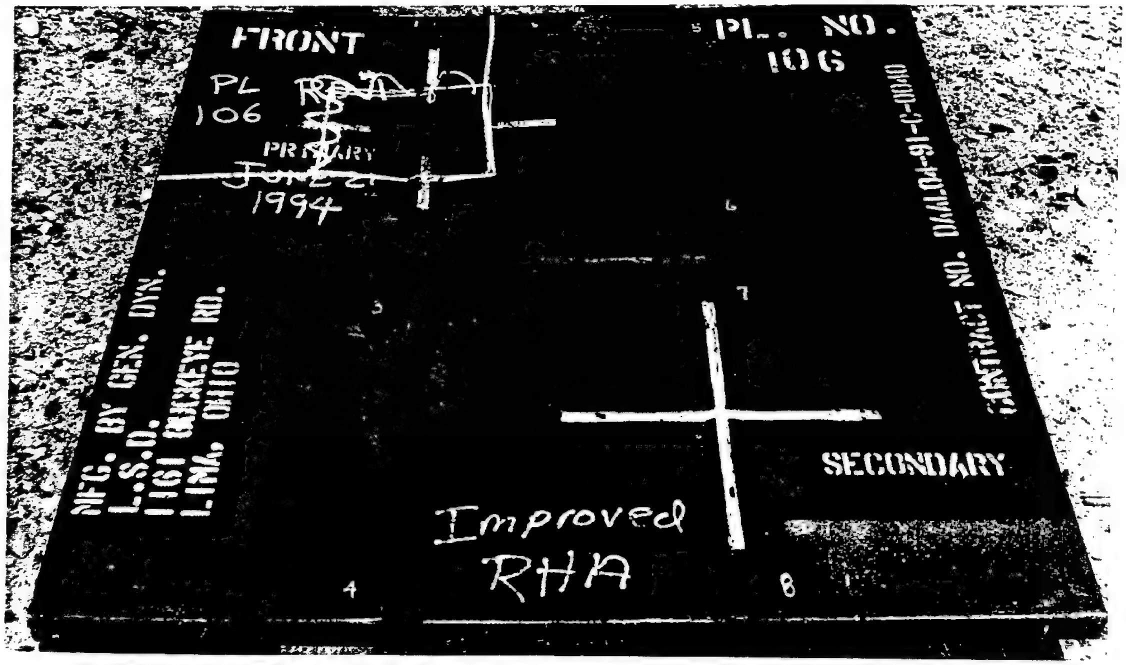
[a] Ballistic tests performed in accordance with MIL-STD-1941 (MR) by ATC; 75-mm M1002 proof projectile.
[b] "Requirements for Ballistic Tests," Table 4, within MIL-STD-1941 (MR), "Metal-Arc Welding of Homogeneous Armor."
[c] IRHA material, USS 200-ton heat, 1 1/2 in thick, HRc 40.
[d] Conventional RHA per MIL-A-12560G, 1 1/2 in thick, HRc 32.

difference from the machining of conventional RHA material. As expected, tool dulling was somewhat more severe for the harder HRc 48 material.

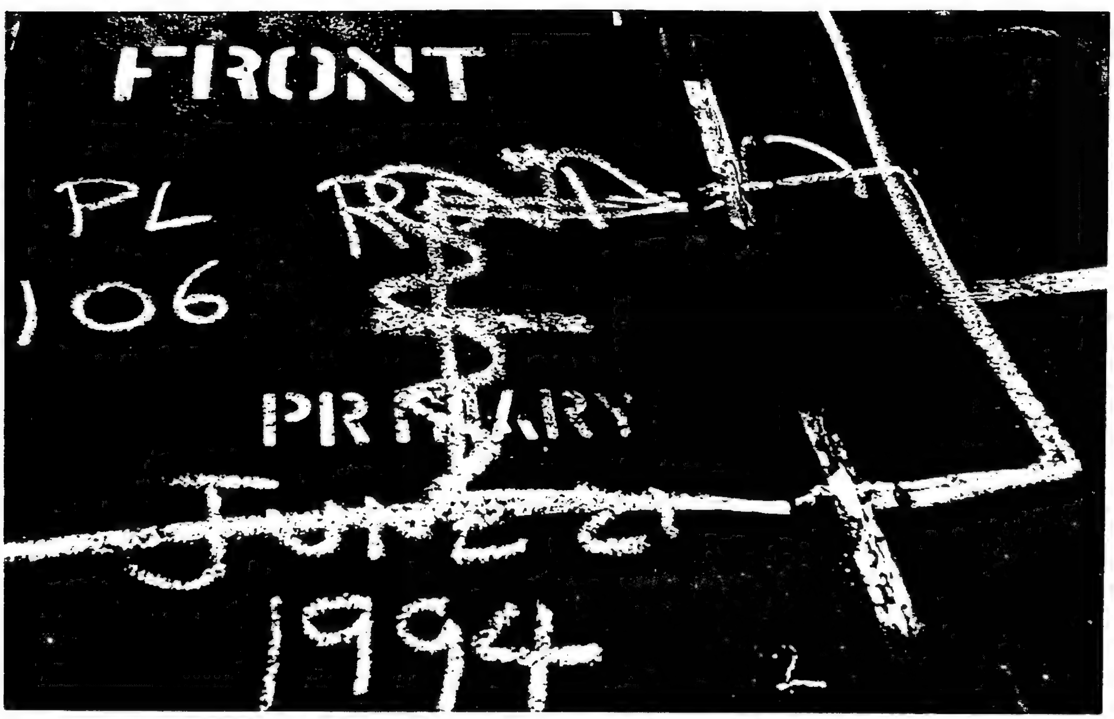
Specifics and detailed test results on the weldability, thermal cutting, and machinability of the IRHA material are documented in the GDLS report under Contract No. DAAL04-91-C-0040 (1994).

7. Conclusions

IRHA steel with enhanced ballistic performance has been achieved through higher hardness. The higher hardness levels (HRc 40 and 48) were accomplished through optimization of a generic RHA Ni-Cr-Mo alloy chemistry and subsequent heat treatment.

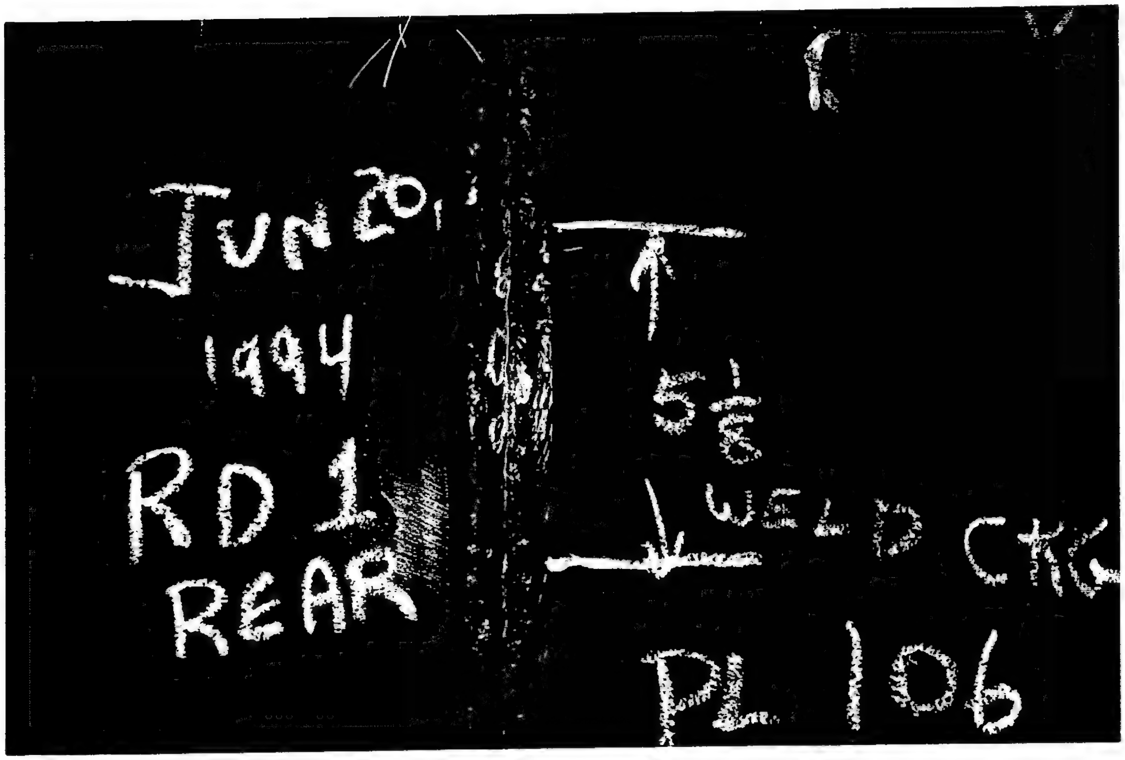


a. Front of the test plate.



b. Closeup of the weld.

Figure 19. Ballistic Test on H-Plate Weldment (USS IRHA 1 1/2-in-Thick Plate; Projectile = 75-mm PP M1002).



c. Back of the test plate.

Figure 19. Ballistic Test on H-Plate Weldment (USS IRHA 1 1/2-in-Thick Plate; Projectile = 75-mm PP M1002) (continued).

The chemical composition of the optimal IRHA alloy in weight-percent is as follows:

Carbon:	0.26	Manganese:	0.40
Nickel:	3.25	Silicon:	0.40
Chromium:	1.45	Phosphorous:	<0.010
Molybdenum:	0.55	Sulfur:	<0.005

Remaining material is basically iron: 93.68
Note that the carbon level should be maintained at 0.24–0.26 for weldability considerations relative to ground combat vehicle structural-ballistic shock requirements.

D_I for the optimal IRHA alloy chemistry is 9.0 to 10.0. It is important that the D_I be greater than 8.0 to ensure through-thickness hardenability for steel plates up to 3 in thick.

To ensure that the desired metallurgical properties are obtained for this up alloyed-higher D_I material, it was determined that the following heat treatment of the rolled plate be required: (1) normalize at 1,700° F and air cool; (2) austenitize at 1,625° F and water-quench; and (3) temper at 985° F to obtain an HRc 40 plate, or temper at 425° F for an HRc 48 plate.

The desired martensitic microstructural content of over 99% was achieved utilizing current production steel mill facilities and practices, including melting, casting, rolling, quenching, and heat treatment. Steel plates tempered to the optimal hardness levels (HRc 40 and 48) maintained the required levels of Charpy impact strength (>20 ft·lb) and toughness.

IRHA provides higher ballistic protection than standard RHA vs. conventional hard steel core AP projectiles, such as the 0.50-cal. APM2. In general, the HRc 48 plate provides higher performance than the HRc 40 material against steel core AP projectiles.

IRHA provides greater ballistic protection than standard RHA against very hard and brittle tungsten carbide penetrators, such as the 20-mm API M602. The IRHA at both the HRc 40 and HRc 48 provides comparable performance vs. this class of penetrators.

IRHA at the HRc 40 level is ballistically equivalent or slightly better than standard RHA vs. FSP/fragmenting munitions, while IRHA at HRc 48 is significantly inferior, due to the premature shear plug failure mode.

In a semi-infinite or applique-type armor configuration, IRHA erodes heavy metal (DU or tungsten alloys) long-rod penetrators more efficiently than standard RHA. Approximately 22% and 14% less penetration is allowed by the IRHA at HRc 48 and HRc 40, respectively.

For combat vehicle hull applications, IRHA at the HRc 40 level is the preferred material, providing the best overall ballistic performance vs. the broad spectrum of projectile/fragment threats.

IRHA at both HRc 40 and 48 passed the 105-mm AP T182 Projectile "Ballistic Shock-Resistance to Cracking" test. Less plate cracking was exhibited by the HRc 40 material.

Weldability and machinability of IRHA at HRc 40 are comparable to standard RHA and passed the welded H-plate ballistic shock-test requirement.

8. Recommendations

It has been recommended that the current RHA specification (MIL-A-12560H) be expanded to include IRHA.

The expanded specification would introduce the IRHA as a Class 4 material as follows: Class 4 - wrought armor plate that is heat treated to higher hardness levels than Class 1 to develop maximum resistance to penetration. <u>This new class of armor is intended for use in combat vehicles; it is not to be used for evaluating ammunition</u>.

Within the new specification, a number of new requirements must be outlined for the Class 4 material, including a minimum D_I of 8.0 with a recommended range of 9.0 to 10.0, and as-quenched hardness of at least HRc 47 for the quenched and draw-tempered (275° F) plate.

The new Class 4 material shall be further specified as Class 4A or 4B:

Class 4A: Tempered to attain a hardness of HRc 47–48, and
Class 4B: Tempered to attain a hardness of HRc 39–41.

Tempering temperatures of 425° F and 985° F should be recommended in the technical notes.

In the technical notes, a recommended Ni-Cr-Mo alloy chemical composition should be included as outlined in the second paragraph of section 7, as well as the heat-treat cycle in the fourth paragraph.

Ballistic Acceptance—to facilitate application of IRHA, the current ballistic requirement tables within MIL-A-12560H can be employed. As material is procured and ballistically tested, a more definitive database will be generated, and new requirements will be established reflecting the material's higher performance.

The Class 4A material tempered to HRc 47–48 hardness level can be used as a surrogate for high hardness steel (HHS) armor (MIL-A-46100). The IRHA at the HRc 47–48 hardness level outperforms HHS at the HRc 49–53 hardness level as required in MIL-A-46100.

9. References

American Society for Testing Materials. "End-Quench Test for Hardenability of Steel." ASTM A255, West Conshohocken, PA, 1995.

Ayvazian, A. M., and D. J. Papetti. "Improved Homogeneous Steel Armor." AMMRC SP73-6, U.S. Army Materials and Mechanics Research Center, Watertown, MA, March 1973.

Campbell, G. M., and A. M. Ayvazian. "Investigation of Low Sulfur, Low Phosphorous, Increased Hardness RHA Steel." AMMRC letter report to the U.S. Army Tank-Automotive Command, Warren, MI, 7 January 1985.

General Dynamics Land Systems. "Improved Hardness RHA Weldability and Material Property Testing." Report 5T-91-23272. Contract No. DAAL04-91-C-0040, December 1994.

Grossman, M. A. "Hardenability Calculated From Chemical Composition." *AIME Proceedings,* The American Institute of Mechanical Engineers, February 1942.

Laible, R. C., et al. *Ballistic Materials and Penetration Mechanics.* New York: Elsevier Scientific Publishing Company, 1980.

Papetti, D. J. "Processing ESR Steel for Improved Homogeneous Armor." AMMRC SP78-4, U.S. Army Materials and Mechanics Research Center, Warren, MI, August 1978.

Society of Automotive Engineers. "Methods of Determining Hardenability of Steels." SAE J406, Warrendale, PA, May 1995.

U.S. Army Materials and Mechanics Research Center. "Armor and Its Applications." In the *Engineering and Design Handbook.* 1971.

U.S. Department of Defense. "Armor Plate, Steel, Wrought, Homogeneous." MIL- A-12560, Washington, D.C.

U.S. Department of Defense. "Armor Plate, Steel, Wrought, High Hardness." MIL-A-46100, Washington, D.C.

INTENTIONALLY LEFT BLANK.

NO. OF COPIES	ORGANIZATION
2	DEFENSE TECHNICAL INFORMATION CENTER DTIC DDA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1	HQDA DAMO FDQ DENNIS SCHMIDT 400 ARMY PENTAGON WASHINGTON DC 20310-0460
1	CECOM SP & TRRSTRL COMMCTN DIV AMSEL RD ST MC M H SOICHER FT MONMOUTH NJ 07703-5203
1	PRIN DPTY FOR TCHNLGY HQ US ARMY MATCOM AMCDCG T M FISETTE 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	PRIN DPTY FOR ACQUSTN HQS US ARMY MATCOM AMCDCG A D ADAMS 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	DPTY CG FOR RDE HQS US ARMY MATCOM AMCRD BG BEAUCHAMP 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	ASST DPTY CG FOR RDE HQS US ARMY MATCOM AMCRD COL S MANESS 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001

NO. OF COPIES	ORGANIZATION
1	DPTY ASSIST SCY FOR R&T SARD TT F MILTON THE PENTAGON RM 3E479 WASHINGTON DC 20310-0103
1	DPTY ASSIST SCY FOR R&T SARD TT D CHAIT THE PENTAGON WASHINGTON DC 20310-0103
1	DPTY ASSIST SCY FOR R&T SARD TT K KOMINOS THE PENTAGON WASHINGTON DC 20310-0103
1	DPTY ASSIST SCY FOR R&T SARD TT B REISMAN THE PENTAGON WASHINGTON DC 20310-0103
1	DPTY ASSIST SCY FOR R&T SARD TT T KILLION THE PENTAGON WASHINGTON DC 20310-0103
1	OSD OUSD(A&T)/ODDDR&E(R) J LUPO THE PENTAGON WASHINGTON DC 20301-7100
1	INST FOR ADVNCD TCHNLGY THE UNIV OF TEXAS AT AUSTIN PO BOX 202797 AUSTIN TX 78720-2797
1	DUSD SPACE 1E765 J G MCNEFF 3900 DEFENSE PENTAGON WASHINGTON DC 20301-3900
1	USAASA MOAS AI W PARRON 9325 GUNSTON RD STE N319 FT BELVOIR VA 22060-5582

NO. OF COPIES	ORGANIZATION
1	CECOM PM GPS COL S YOUNG FT MONMOUTH NJ 07703
1	GPS JOINT PROG OFC DIR COL J CLAY 2435 VELA WAY STE 1613 LOS ANGELES AFB CA 90245-5500
1	ELECTRONIC SYS DIV DIR CECOM RDEC J NIEMELA FT MONMOUTH NJ 07703
3	DARPA L STOTTS J PENNELLA B KASPAR 3701 N FAIRFAX DR ARLINGTON VA 22203-1714
1	SPCL ASST TO WING CMNDR 50SW/CCX CAPT P H BERNSTEIN 300 O'MALLEY AVE STE 20 FALCON AFB CO 80912-3020
1	USAF SMC/CED DMA/JPO M ISON 2435 VELA WAY STE 1613 LOS ANGELES AFB CA 90245-5500
1	US MILITARY ACADEMY MATH SCI CTR OF EXCELLENCE DEPT OF MATHEMATICAL SCI MDN A MAJ DON ENGEN THAYER HALL WEST POINT NY 10996-1786
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CS AL TP 2800 POWDER MILL RD ADELPHI MD 20783-1145

NO. OF COPIES	ORGANIZATION
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CS AL TA 2800 POWDER MILL RD ADELPHI MD 20783-1145
3	DIRECTOR US ARMY RESEARCH LAB AMSRL CI LL 2800 POWDER MILL RD ADELPHI MD 20783-1145

ABERDEEN PROVING GROUND

NO. OF COPIES	ORGANIZATION
2	DIR USARL AMSRL CI LP (305)

NO. OF COPIES	ORGANIZATION
1	OUSD RE THE PENTAGON WASHINGTON DC 20301
1	DIR DIA ODT 5A F JAEGER WASHINGTON DC 20340-6053
2	CDR DTIC FDAC 5010 DUKE ST CMRN STN BLDG 5 ALEXANDRIA VA 23304-6145
1	CDR AMC AMCSCI 5001 ESNHWR AVE ALEXANDRIA VA 22333
4	DIR ARL AMSRL OP SD TP TECH PUBLISHING BR AMSRL OP SD TA RECORDS MGMT AMSRL OP SD TL TECH LIB AMSRL SS 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	DIR ARL ELCTRNC PWR SRCS DIR TECH LIB FORT MONMOUTH NJ 07703
1	CDR ARO INFO PRCSNG OFC PO BOX 12211 RESEARCH TRIANGLE PARK NC 27709-2211
1	CDR USA MRDEC AMSMR RD CS R DOC REDSTONE ARSENAL AL 35809
2	CDR USA TACOM AMSTA ZSK AMSTA TSL TECH LIB WARREN MI 48397-5000

NO. OF COPIES	ORGANIZATION
1	CDR USA ARDEC TECH LIB DOVER NJ 07801
6	OFFICE OF THE PM GROUND SYSTEMS INTEGRATION SFAE GLSS W GSI H T DEAN WARREN MI 48397-5000
4	DIR BENET WPNS LAB AMSTA AR LCB TL AMSTA AR LCB R AMSTA AR LCB RM AMSTA AR LCB RP WATERVLIET NY 12189
1	CDR USA CMNCTNS & ELEC CMD TECH LIB FORT MONMOUTH NJ 07703
1	CDR USA NATICK RDE CTR SATNC MI TECH LIB NATICK MA 01760-5010
1	CDR DPG TECH INFO DIV TECH LIB DUGWAY PROVING GROUND UT 84022
3	CDR NGIC AIFRTC APPLIED TECH BR G SCHLESINGER 220 7TH ST NE CHARLOTTESVILLE VA 22901-5396
1	CDR USA ARU TECH LIB PO BOX 577 FORT RUCKER AL 36360
1	CDR USA AVN TRNG LIB BLDG 5906-5907 FORT RUCKER AL 36360

NO. OF COPIES	ORGANIZATION
1	CDR USA AAS TECH LIB FORT RUCKER AL 36360
1	CDR USA SCA TECH DCMNT CTR FORT MONMOUTH NJ 07703
1	CDR USA ENGNRNG WTRWYS EXPRMNTL STN RSRCH CTR LIB PO BOX 631 VICKSBURG MS 39180
1	USA VHCL PRPLSN DRCTRT NASA LEWIS RSRCH CTR AMSRL VP 2100 BROOKPARK RD CLEVELAND OH 44135-3191
1	PRSDNT USA AESWB LIBRARY FORT BRAGG NC 28307
1	CMDT USA QRTRMSTR SCHL SCHL LIB FORT LEE VA 23801
1	CDR CLRK ENG SCHL LBRY 3202 NEBRASKA AVE N FORT LEONARDWOOD MO 65473-5000
1	DIR USA ARTA LANGLEY RSRCH CTR MS-266 AVSCOM HAMPTON VA 23665-5225
1	NRL CODE 6384 WASHINGTON DC 20375
1	CHF OF NVL RSRCH CODE 471 ARLINGTON VA 22217

NO. OF COPIES	ORGANIZATION
1	COM ON MRN STRCTRS USMC BOARD NRC 2101 CNSTTTN AVE NW WASHINGTON DC 20418
2	CDR USAF WRDC MLLP M FORNEY JR MLBC S SCHULMAN WRIGHT-PATTERSON AFB OH 45433-6523
1	NASA LANGLEY RSRCH CTR HAMPTON VA 23665-5255
1	CHRLS STRK DRPR LAB 555 TECH SQ CAMBRIDGE MA 02139
1	NIST S M HSUCRMCS DIV INST FOR MTRLS SCNC & ENGNRNG GAITHERSBURG MD 20899
1	MIA CINDAS PURDUE UNIVERSITY 2595 YEAGER RD WEST LAFAYETTE IN 47905
1	GNRL DYNMCS CNVR ARSPC DIV MFG ENG TECH LIB PO BOX 748 FORT WORTH TX 76101
1	MTRLS SCI CORP 500 OFC CTR DR STE 250 FORT WASHINGTON PA 19034

ABERDEEN PROVING GROUND

NO. OF COPIES	ORGANIZATION
1	DIR AMSAA AMXSY MP H COHEN
22	DIR ARL AMSRL WM AMSRL WM MF, R SQUILLACIOTI (20 CPS)

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 1997	Final, October 1989 - September 1995

4. TITLE AND SUBTITLE

Improved Rolled Homogeneous Armor (IRHA) Steel Through Higher Hardness

5. FUNDING NUMBERS

78M462

6. AUTHOR(S)

Joseph Prifti, Michael Castro, Richard Squillacioti, and Raymond Cellitti*

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Research Laboratory
ATTN: AMSRL-WM-MF
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER

ARL-TR-1347

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10.SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

The POC is Dr. Shun-Chin Chou, AMSRL-WM-MF, APG, MD 21005-5069.
*Mr. Cellitti works for R. C. Associates, 122 Columbia, Hinsdale, IL 60521.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

An improved rolled homogeneous armor (IRHA) steel with enhanced ballistic performance has been developed. Increases in ballistic performance are attributed to higher hardness levels achieved by IRHA, which maintain adequate toughness and ductility. Through augmentation of a generic chemical composition for standard rolled homogeneous armor (RHA) material, and optimization of heat treatment, greater hardenability, and higher hardness levels were attained. The higher hardenability ensures that through-thickness hardness, with the desired martensite microstructure, is obtained for armor plates up to 3 in thick, using current steel mill facilities and practice. The optimal, relatively low-carbon, nickel-chromium-molybdenum (Ni-Cr-Mo) IRHA alloy was developed in-house, employing U.S. Army Research Laboratory (ARL), Materials Directorate (MD) laboratory facilities, followed by steel mill production heats demonstrating scale-up and producibility. Ballistic testing vs. projectiles, ranging from medium caliber to tank rounds, established that the IRHA material at the HRc 40 hardness level is best suited for vehicle hull applications, while material at HRc 48 provides better protection as applique armor. The armor plate at both hardness levels (HRc 40 and 48) demonstrated structural integrity upon high kinetic energy (KE) ballistic loading, through passing the required full-scale 105-mm armor piercing (AP) T182 projectile impact tests. At the HRc 40 level, the IRHA weldability and fabricability were shown to be comparable to standard RHA for tank construction.

14. SUBJECT TERMS

armor, steel, rolled homogeneous armor (RHA,) structural armor, applique armor

15. NUMBER OF PAGES

51

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

INTENTIONALLY LEFT BLANK.

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number/Author ARL-TR-1347 (Prifti) ____________ Date of Report April 1997 ________

2. Date Report Received ____

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) ____

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) ________

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. ____________________

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) ____________________

CURRENT ADDRESS

Organization

Name E-mail Name

Street or P.O. Box No.

City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

OLD ADDRESS

Organization

Name

Street or P.O. Box No.

City, State, Zip Code

(Remove this sheet, fold as indicated, tape closed, and mail.)

(DO NOT STAPLE)